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A severe tornado obliterates a house near Mulvane, Kansas, June 12, 2004. More than 1,000 tornados occur each year in the U.S.
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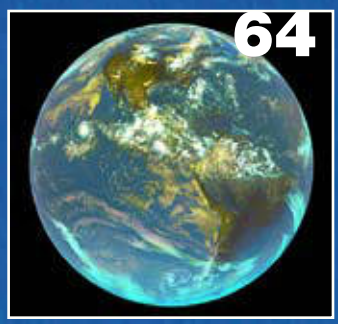

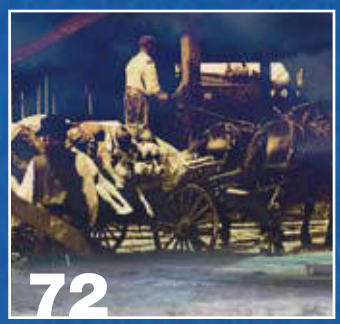

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Welcome to *Extreme Weather*

Weather seems to be on our minds more with every passing day.

News shows report on extreme or severe weather from around the country, covering tornados, hurricanes, blizzards, mudslides, dust storms, heat waves, and intense thunderstorms. Weather has become much more than a barometer of how to dress for the day. It's about long-term adaptation and survival, how climate change is altering our planet, and awareness of our influence on Earth's atmosphere — for better or worse.

With this consciousness in mind, *Astronomy* magazine's staff brings you *Extreme Weather*. This special issue contains stories focusing on the most amazing aspects of this topic. The articles contain up-to-the-minute science behind the weather, spectacular photos, and in-depth diagrams in keeping with *Astronomy*'s award-winning coverage of the cosmos.

In "Chasing the perfect storm" (page 8), we invite you to join world-renowned storm tracker Warren Faidley as he pursues twisters armed with adrenaline, a laptop, and photographic equipment. His recount of the tornado of May 4, 2007, in Greensburg, Kansas, is a chilling, gripping read that will put you at the center of the action.

Mother Nature's hazards are not restricted to monster storms. In "Nature's wicked spark" (page 34), Senor Editor Francis Reddy explains why lightning is beautiful, deadly, and packed with secrets scientists would love to unlock. In the past 25 years, researchers have found that aircraft can trigger lightning and that previously unseen forms of lightning exist.

Reddy also illustrates the peculiar, powerful process that builds supercell storms in "When thunderstorms turn deadly" (page 52). To demonstrate how ordinary thunderstorms can be supercharged, Reddy examines the La Plata, Maryland, storm of April 28, 2002. The story features the physics of high-energy clouds and the people on the ground who reacted, plotted, and warned others of the coming danger.

Of all weather-related subjects, none is more current or controversial than global warming. In "Can we live with climate change?" (page 26), Robert Henson, a writer and editor at the University Corporation for Atmospheric Research, lays down the scientific story of what we know. Politics aside, Earth in 50 years will be a different place. Henson forecasts what is coming and how we can handle a changing world.

"Is global warming unleashing more powerful hurricanes?" by Associate Editor Daniel Pendick (page 16) investigates a fear of many weather researchers: that future hurricanes will be much stronger. Following Katrina and the destruction in New Orleans, the effect of climate change on hurricanes was dramatically pushed forward as a scientific area of study.

Pendick also looks back at the United States' greatest weather tragedy: the 1900 Galveston, Texas, hurricane. "How Galveston survived America's deadliest storm" (page 72) describes how low-lying land, dense development, and little warning led to the deaths of at least 6,000 people — perhaps as many as 10,000.

I hope you will enjoy *Extreme Weather*'s unique blend of weather science, images, and graphics. Please let me know what you think at editor@astronomy.com.

Yours truly,

David J. Eicher
Editor

EXTREME WEATHER

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A field guide to CLOUDS

All clouds form the same way, but their different appearances tell you what weather will follow.

By Laura Baird

Whether tranquil or menacing, clouds are clues about what weather is in store. White, puffy clouds floating on gentle breezes usually signal fair weather. Gray sheets of clouds that block out the Sun often foretell heavy storms. Even the casual observer recognizes as much, but did you know there are 10 basic cloud types classified according to appearance and height above sea level?

Stratus, cumulus, stratocumulus, and nimbostratus clouds form at altitudes below 8,000 feet (2,440 meters). In Latin, *stratus* means layer-like, which aptly describes the uniform gray of an overcast sky. Usually created when layers of different air temperatures meet, stratus clouds can drizzle.

Cumulus clouds, however, usually do not produce precipitation. Their flat bottoms indicate where the dew point is in the atmosphere — where the air is saturated and water vapor condenses. Their cotton-ball-like tops adopt ever-changing shapes fascinating to watch.

Stacked in layers, cumulus clouds form stratocumulus clouds, with dark bottoms and irregular edges. Finally, thick nimbostratus clouds rain heavily.

The middle family of clouds includes those between 6,000 and 20,000 feet (1,830 and 6,100m) above sea level. Altocumulus clouds are small puffs that often appear in rows, while altostratus clouds are so thin, sometimes they don't cast shadows.

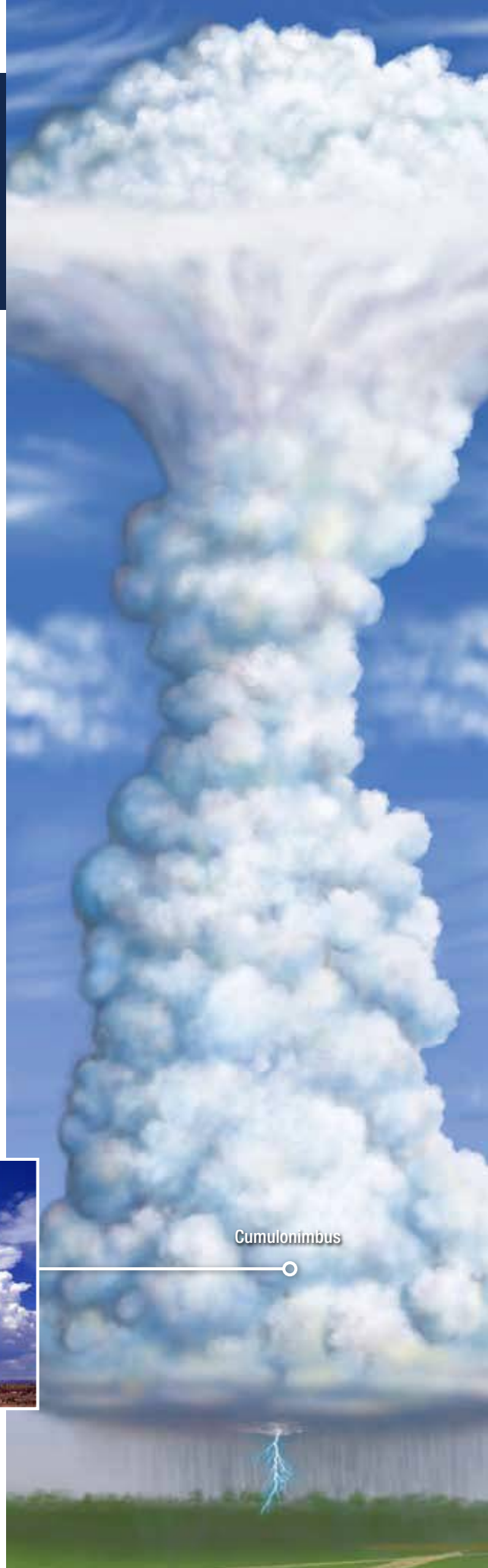
Above 20,000 feet, clouds are made of ice crystals. *Cirrus* in Latin means "curl," which describes the undulations of these high-flying clouds. Cirrocumulus clouds resemble waves in the sky. Their rippled appearance indicates turbulence, and usually means a warm front is moving in. Translucent sheets of cirrostratus clouds, on the other hand, may cover the sky and warn of an approaching storm.

The most threatening clouds, though, are cumulonimbus. Merging cumulus clouds produce these giants, which can reach 70,000 feet (21,300m) above sea level at their most extreme. When the growing cloud reaches the upper atmosphere, ice forms the distinctive anvil-shaped top.

Despite their apparent differences, all clouds form the same way. As air heated at the surface rises and cools, ever-present water vapor changes into liquid, which sticks to microscopic pollutants in the air. Tiny droplets clump together and, eventually, become visible as clouds.

Air forced upward by mountains, incoming weather fronts, or colliding air masses (like where the trade winds meet at the equator) can also produce clouds. Characteristics of the air before the lifting occurs influence what type of cloud forms. Whether clouds release rain depends on how much moisture collects and how high the clouds are.

Cumulonimbus clouds spawn violent storms, including tornados. The anvil-shaped tops form where ice condenses in the upper atmosphere.



Cirrus

Ice crystals comprise high-flying, curl-like cirrus clouds.

Cirrocumulus

The wave-like look of cirrocumulus clouds indicates turbulence.

Cirrostratus

Translucent cirrostratus clouds can mean stormy weather's on the way.

20,000 feet (6,100 meters) above sea level

Altocumulus

Rows of altocumulus clouds often appear before a cold front.

The Sun can usually poke through thin, wispy altostratus clouds.

Altostratus

8,000 feet (2,440 meters) above sea level

Stratocumulus

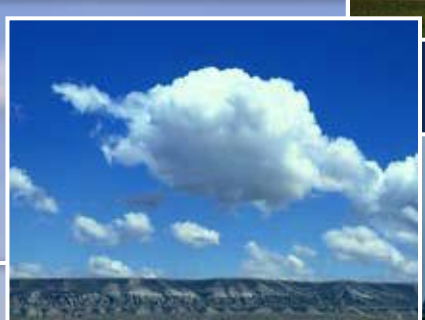
Horizontal "ribbons" of stratocumulus clouds often clump together.

Rain is imminent when thick sheets of nimbostratus clouds appear.

Nimbostratus

Stratus

Cumulus



Many summer days sport puffy cumulus clouds drifting overhead.

The ill-defined edges of stratus clouds create gray, overcast skies.

Chasing the perfect storm

Ride along as legendary storm tracker Warren Faidley searches for the world's most dangerous photo opportunity.

By Warren Faidley

FAIDLEY keeps in continuous contact with weather forecasters, and he checks maps and GPS readouts to confirm his locations. WARREN FAIDLEY

ANYONE WHO HAD LIVED IN GREENSBURG, KANSAS, for any length of time knew something was amiss May 4, 2007. The usual twilight was missing from the sky. Not a single star was visible, all lost in a sea of darkness. An unnerving energy filled the air as rumbles of thunder boomed and echoed through rows of small homes. Springtime thunderstorms were common, but this one was different.

Flashes of neon-white lightning occasionally illuminated the storm's underside, revealing cloud formations cast in eerie shadows of gray and black. With every boom and shake of thunder, the darkness deepened and edged closer.

PROFESSIONAL STORM CHASER
Warren Faidley tracks violent storms in his specially equipped vehicle, hoping to score the perfect tornado photo or video.
WARREN FAIDLEY

A few people milled outside their homes, warily monitoring the storm's progress. Some moved their vehicles under carports to avoid hail. Others perched close to their televisions and radios, listening to the weather reports.

Around 9:30 P.M., fingers of vaporous clouds began to touch down on the southwest side of town. Within minutes, the lowering cloud base congealed into a ragged collar nearly a mile wide, rotating and drawing in dust. To the trained storm spotter or weather-savvy citizen, this was a horrifying sight — the unmistakable sign of a massive tornado forming.

Greensburg was in serious peril. No technology or human action could prevent the disaster from unfolding.

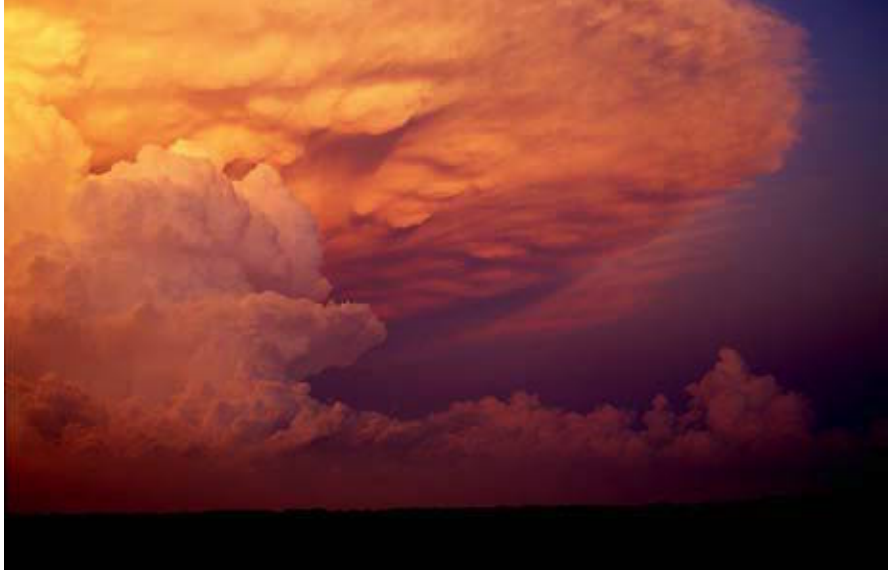
Sky watching

Imminent violence and destruction were not at the forefront of my mind earlier that day. I sat in my parked storm-chasing vehicle on a Texas hilltop, about 125 miles (200 kilometers) southwest of Greensburg. But I was keenly aware of the possibility of a dangerous storm or even a violent tornado. The atmosphere was, without question, extremely unstable and primed to explode.

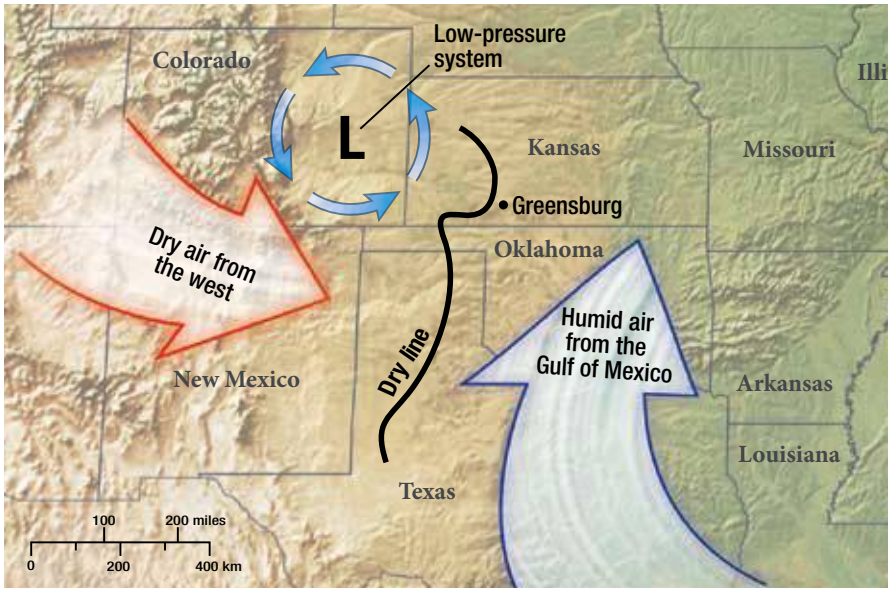
For the moment, all was tranquil. Only a few puffy-white cumulus clouds drifted harmlessly overhead. It was only a few ticks past 4 P.M. As I downloaded weather data onto my laptop via a cell phone connection, I saw nothing unusual in the sky. It usually took a full day of surface heating for the atmosphere to become unstable enough to spawn thunderstorms.

When the seeming calm broke, warm, moist air would break through into the cooler air aloft. Billowy white cumulus cloud "towers" would form as the moisture began to condense into tiny droplets. If the tower could develop enough upward momentum, it would evolve into a thunderstorm — drawing in moist-air "fuel" from ground level and transforming it into driving rain and hail.

But a tornado-prone storm requires more. Two key ingredients are a shift in wind direction and increasing wind speed with altitude. This induces rotation in the storm's core, sculpting it into a "supercell." Characterized by softball-sized



HIGHER AND HIGHER, the storm's core rockets upward until it hits the stratosphere's cold base. There, it loses buoyancy and spreads out to form a characteristic anvil-like cap. WARREN FAIDLEY



ON MAY 4, 2007, conditions favored growth of supercell storms in Kansas and Oklahoma. A trough of low pressure approached from the west, which helped to lift warm moist air flowing in from the south and spawn storm clouds. Storms were most likely to form east of the "dry line." The dry line marks an unstable atmospheric boundary where pressure and humidity change rapidly. *EXTREME WEATHER:* ROEN KELLY

STORMS that don't drop funnels can still be extremely hazardous, producing golfball-sized hail and torrential rain. WARREN FAIDLEY

hailstones, heavy rain, violent winds, and sometimes tornados, supercell storms are a chaser's ultimate prey.

Elements were present May 4 to enhance the formation of supercells. A trough of low pressure was approaching from the west. This would help lift warm air and initiate convection. Also, to the west of my location, an unstable boundary lay in the lower atmosphere called the "dry line." This boundary marked the line between dry air to the west and moist air flowing in from the Gulf of Mexico. I kept a close eye on that line. Storms would tend to form east of it — right where I was waiting.

Mean season

I had reason for hope of chasing a major storm today. It was the height of the 2007 storm season, with at least 10 tornado outbreaks already on record. More than 30 people had been killed since January 1 — greater than twice the average toll for the previous 3 years.

The most devastating outbreak occurred from February 28 through March 2, when a swarm of 49 tornados struck the central and southeastern United States. On March 1, a monstrous twister struck a high school in Enterprise, Alabama, killing 9. On the Enhanced Fujita (EF) tornado intensity scale, this twister scored an EF4, one category below the highest possible rating of 5. So 2007 was already a deadly season.

Late in the afternoon May 4, my vantage point off Highway 83 in northeastern Texas offered a spectacular view. All I could see were flowing green fields fading off into endless horizons. Such a vast, open area is where storm chasers enjoy the best visibility. On plains mostly flat as a pancake, you can see a storm forming more than a hundred miles away.

Many of the earlier outbreaks occurred in the deep South or in areas where vegetation and/or terrain limits one's ability to see or photograph. I avoid those areas. On the plains of Tornado Alley, no storm tower exploding upward will go unnoticed — or unchased — today.

I've captured a few tornados this year, but nothing spectacular. My annual quest to find the perfect storm picture is unfulfilled so far. On April 21, I intercepted two tornados northwest of Lubbock, Texas. Neither of these twisters proved to be a good subject. Each was either too far away or lost in heavy rain. For a journalist and photographer who earns his living from a potpourri of severe weather-related enterprises, days like today come only a few times a year.

WARREN FAIDLEY first captured the Arnett tornado May 4 as it tracked due east toward Highway 283 in Oklahoma. WARREN FAIDLEY

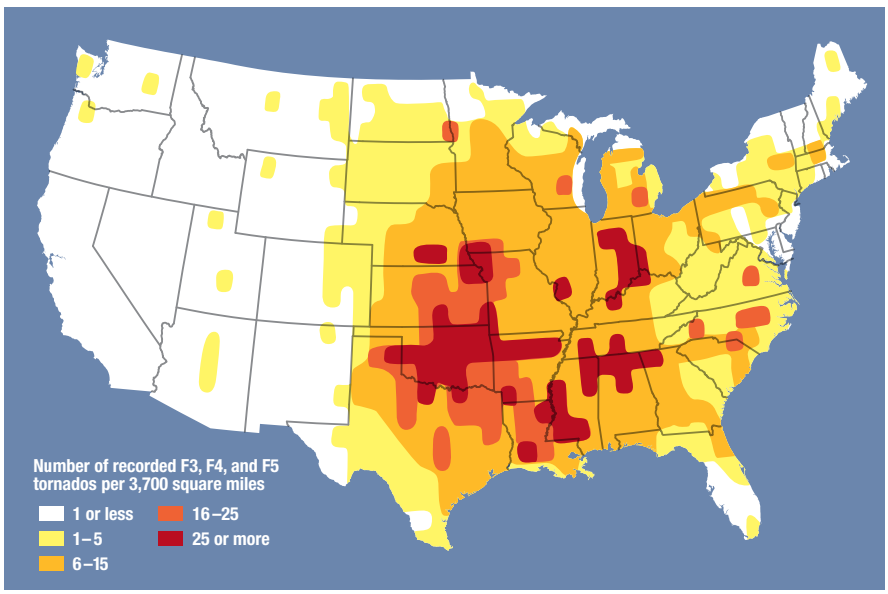
Waiting for action

I'm anxious, but also seasoned with patience. In 20 years of chasing, I've spent many days waiting for nothing to happen. I chew on a couple of watermelon hard candies and down a soda. I'm waiting for the adrenalin rush to come — or not.

My boredom is cut short when motion draws my attention toward the southeast. The first signs of trouble have arrived. Tall, dense storm towers skyrocket into the sky like atomic mushroom clouds. I began to get that old familiar feeling. All hell is about to break loose.

I check my GPS unit to confirm potential road routes toward the developing storm. I check everything three times. Sunset will come at 8:19 P.M., so I've got about 4 hours to chase — not a lot of time. After dark, chasing is suicide. The only way to see a tornado after dark is between lightning flashes — even worse, to hear it. It could be the last thing you hear.

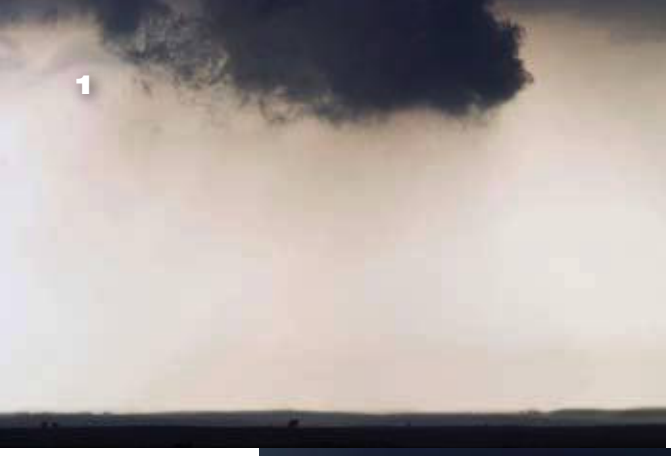
I plot several courses. I can easily move to the south, north, or east. I don't just blast off after the first cloud. A towering cumulus does not always become a storm.



TORNADO ALLEY refers to the south-central portion of the United States that experiences the most tornado activity in the country. Meteorological conditions in the Alley favor formation of large, long-lived storms, called supercells. These spawn the most damaging tornados. *EXTREME WEATHER:* ROEN KELLY

I continue to scan the horizon from the northeast to the southeast. I log onto my laptop via a cell phone link and check the meteorological data one last time.

The first item I download is the latest forecast issued by the U.S. government's Storm Prediction Center in Norman, Oklahoma. Issued several times daily, "severe weather outlooks" identify areas of possible severe weather. My area of interest is included in a "moderate risk" region of severe weather, with the possibility of "rapidly forming severe storms, large and damaging hail, and tornados."



1. A CIRCULAR "WALL CLOUD" dangles from the storm, signaling the core of powerful updrafts converging to become a tornado. ALL PHOTOS: WARREN FAIDLEY

2. CIRCULATION beneath the funnel-shaped base under the storm signals tornado formation.

3. THE TORNADO becomes a classic *Wizard of Oz* twister as Faidley zooms in, snapping photo after photo as quickly as possible.

Tornado totals for 2007

Month	Total	3-year average (confirmed)
January	21	34
February	52	25
March	171	128
April	165	181
May	251	171
June	128	188
July	69	93
August	73	92
September	51	89
October	87	60
November	6	66
December	22*	33
TOTAL	1,096	1,159

* PRELIMINARY TOTAL.
SOURCE: U.S. WEATHER SERVICE STORM PREDICTION CENTER: WWW.SPC.NOAA.GOV

The 2007 winter/spring storm season

From January to June 2007, weather authorities recorded 788 tornados. The 3-year average for the same period was 727 tornados. Severe storms killed 22 people from January through June 2007. This includes one person who died in September from injuries sustained earlier in the year in the Greensburg, Kansas, tornado (May 4). The average number of deaths for the 3-year period, 2004-2006, was 13.

A special notation includes: "Strong tornados possible in southwestern Kansas."

Just as I log off, more equally interesting clouds begin to tower in the northeast. I check the radar — nothing yet.

Another group of chasers passes by on the main highway below, racing toward the southeast. The towers have lured them like the Pied Piper. I still wait. I cannot let anything change my own decisions. This is how I've screwed up before. Once I commit to an area, it's very difficult to switch to another before sunset.

I glance again to the northeast. One of the cloud towers rises upward and fans out in the likeness of a dragon's head with its mouth wide open.

Clumps of storm towers to the southeast still look promising. I estimate they sit somewhere near the Texas and Oklahoma border. A vast network of highways and country roads covers this area.

The storms trying to form to my northeast also are moving into a network of roads in southwestern Kansas. I realize heading east to transect a northeast moving storm will be easier than heading northeast to play catch-up. If a storm forms, it will move at 40 mph or faster. I still can head that way, but I must decide quickly or both options will fade.

The chase begins

I make the decision and pull onto the highway. My choice will dictate failure or success — even life or death — but I can wait no longer. The clouds to the southeast are blooming rapidly into a storm. I work my way southeast toward the Oklahoma and Texas border. The 70-mph speed limits on Texas highways are a godsend for chasing. Although I'm in no hurry now, I might need such speed later.

In less than an hour, the sky's towering cumulus clouds have become a dangerous supercell storm. At 5:42 P.M., my weather radio signals a Severe Thunderstorm Warning for Ellis County, Oklahoma. Doppler radar reports indicate "hail to the size of golf balls and winds of more than 65 mph are likely."

Using my GPS unit with a Doppler radar overlay, I route myself along Highway 283 in Oklahoma toward the southwestern quadrant of the storm. It is within this region of the storm where updrafts form and tornados are most likely. Moment by moment, the storm

4. THE FUNNEL-SHAPED TORNADO assumes a ropey shape and finally dissipates. The thunderstorm that spawned the twister continues to lash the countryside.

5. THE STORM TRACKS northeast from Faidley's location at 40 mph, dragging the sinewy twister across the landscape.

becomes more organized and develops the potential to spawn tornados.

A glance reveals that the top of the storm has rocketed above 40,000 feet (12,200 meters). Its base, where the storm ingests warm air fuel, has flattened. A roundish mass called a wall cloud hangs below the base. A wall cloud often means a tornado is imminent.

I race northward to position myself slightly to the right side of the base. I do not want to drive too far north or I'll run into the leading edge of hail and rain — or place myself in the tornado's path.

Photo op

Within minutes, a cone-shaped funnel cloud drops from the base. I quickly scan the left side of the road for a vantage point. I need a clear shot of the base with good contrast and a clear foreground.

I pull off the main highway onto a dirt road. I must be careful. The thick red Oklahoma mud is like storm-chaser flypaper. I quickly set up my high-definition video camera as the show unfolds.

The funnel cloud begins sucking up debris and dust. Once this earthly contact is made, the funnel officially becomes a tornado. No sooner, the weather radio alarm goes off: TORNADO WARNING. This is good for me. As a storm spotter, I will not need to call in a report.

I work quickly, by instinct. The video camera is rolling. Yes! Checked it twice. It's rolling. The little red light is on. I've made the mistake before of accidentally turning it on, then off.

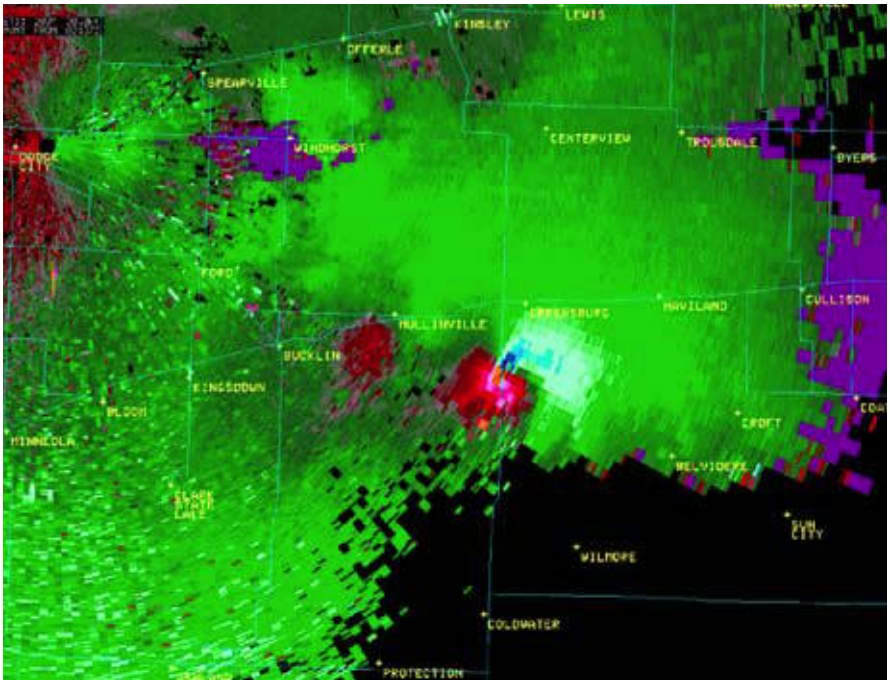
I grab my digital and film cameras. I fire off frames like a machine gun. I take tight shots, vertical shots, horizontals, and wide angles. I know most tornados last less than 10 minutes.

This one is a classic, a long, sinewy twister dancing beneath the storm base. It's a *Wizard of Oz* look-alike. My heart is pounding.

An Oklahoma Highway Patrol car stops on the highway near me. "Which way is it heading?" the officer asks. "Northeast at 35 to 40 mph," I yell over. He blasts off with lights flashing.

Even though I'm shooting pictures like a man possessed, I'm subconsciously aware of the tornado's track. Fortunately, this one is over open country. My tornado is a subject of art right now. If it starts heading toward a populated area, it will be a different story. My excitement would be muffled. My pursuit would become a subject of journalism — and possibly rescue. (I'm also an EMT.)

For more than 20 minutes, I document the storm along Highway 283. It's now



DOPPLER RADAR DETECTS WIND as well as rain. In this radar image, the white blob passing over Greensburg, Kansas, signifies the storm's powerful rotating core. The storm spawned a tornado that virtually destroyed Greensburg May 4, 2007, and killed 11 people. NOAA

MORE THAN A MILE WIDE, the Greensburg tornado destroyed 95 percent of the Kansas town. Ten people died that night; one more died later from injuries sustained during the tornado. GREG HENSHALL (FEMA)

after 6 P.M. Time flies by when the game is afoot. Fortunately for the town of Arnett, Oklahoma — previously in the direct path of the twister — the tornado dissipates and misses it. Most tornados skirt populated areas, but sometimes by the narrowest of margins.

In a storm's shadow

Even though the tornado has dissipated, this is still a dangerous storm. On such unstable and dynamic weather days, storms often pulse, producing multiple or unusually long-lived tornados. The infamous Tri-State tornado outbreak of March 18, 1925, left paths of destruction totaling about 219 miles (350 km) and lasted for more than 3.5 hours.

I shadow the storm northeastward, strategically maintaining a favorable position to its southeast in case I get the chance to shoot another tornado. Suddenly, I realize the storm is moving toward Woodward, Oklahoma, which has a population of about 12,000. According to my GPS mapping, the storm's core will pass close to the town.

Fortunately, the tempest has lost some of its earlier structure and punch. The organized, flat base and wall cloud have diminished. The telltale signs of rotation — tail-like clouds feeding into the lower portions of the storm — have vanished.

Driving toward Woodward, I glance out at the far northern horizon. I can see the golden top of a massive storm bathed in the setting Sun. Although the storm is more than 80 miles (128 km) distant, I can see it is a powerful one.

I fear the people in Kansas are going to have a rough night. Unfortunately, I was right. That early evening storm was headed for Greensburg, Kansas.

Woodward lucks out

Arriving in Woodward, I am pleased to see that it is relatively unscathed. The only damage appears to be from hail and heavy rain. I stop along the highway to photograph the hailstones. Several kids try to juggle baseball-sized stones in front of their home across the highway.

I follow the storm a few miles east of Woodward until the fading Sun finally limits my visibility. Roadway debris, heavy rain, and free-roaming cattle make for hazardous driving at night. I'm done. No need to push it.

It's been a long and productive day. I'll stay the night in Woodward and plan for tomorrow. I grab the last room at an upscale hotel. I'll pamper myself tonight.

After I quickly organize my equipment, I experience a sudden drop in adrenalin. I've hit the wall. I begin to play back the last few hours' events in my head like a movie. This is the time when I come off autopilot and suddenly discover any mistakes, like an incorrect camera setting or equipment left behind.

Once I've satisfied my mind's inquisition, a beer and pizza sound great. I've captured a stunning tornado and no one was hurt. It is a time to relax and celebrate my good fortune — and Woodward's.

When I return to my room, news is breaking of a tornado strike in Greensburg, Kansas. The dragon's head-shaped clouds I had decided earlier not to chase toward the northeast have become a real monster storm. Like many news stories, the magnitude of the disaster is unknown until the next morning.

The Greensburg disaster

About the same time I was unloading and checking my gear in Woodward, storm spotters and chasers around Greensburg were reporting the formation of a large tornado. The supercell that spawned the

TORNADO TALK

EF scale
The Enhanced Fujita (EF) scale rates a tornado's intensity according to its maximum wind speed and the damage it causes to human structures and vegetation. The scale runs from EF1 (lowest intensity) to EF5 (highest).

Severe thunderstorm warning
The National Weather Service issues a severe thunderstorm warning when a thunderstorm produces hail ¾" or larger in diameter and/or winds of 58 mph or higher. Radar data also may warrant a warning.

Tornado watch
Meteorologists issue a tornado watch when conditions are favorable for the development of severe thunderstorms that could produce tornados. The tornado watch identifies a relatively large geographical area in which tornados are possible.

Tornado warning
The NWS issues a tornado warning after someone sights a tornado, either by direct observation or on Doppler radar. A warning may also occur if someone observes highly probable signs of an imminent tornado, such as a funnel or wall cloud beneath a storm, or signs of rotation inside a strong thunderstorm observed on Doppler radar.

GREENSBURG RESIDENTS pinned a flag to one of the few trees left standing in the devastated zone. The town of fewer than 1,500 people faces years of rebuilding. TIM TYSON (FEMA)

twister began as the tower of cumulus clouds I watched from my hilltop perch earlier in the day.

At 6:15 P.M., the National Weather Service (NWS) had issued a tornado watch. This meant conditions were favorable for the development of severe thunderstorms that could produce tornados.

The first tornado warning went out at 8:35 p.m. for Clark County, Kansas. The warning meant somebody had spotted an actual twister. The Dodge City NWS branch issued at least four additional tornado warnings as the storm approached Greensburg, providing time for people to find shelter or leave the area.

Around 9:30 P.M., multiple storm chasers and storm spotters reported the formation of a tornado southwest of Greensburg. Armchair chasers around the country, watching high-resolution Doppler radar from home, posted ominous blog entries proclaiming "the imminent destruction of Greensburg."

Within 8 minutes of the initial sightings, observers reported a very large tornado, estimated at more than a mile wide. Greensburg was only moments away from annihilation. Anyone not in an underground shelter was in grave peril.

The tornado grew even larger and more intense as it churned across the center of Greensburg, expanding to about 1.7 miles (2.7 km) across. It transformed 95 percent of the town into a swirling mass of debris. The town center looked like a bombed-out war zone. Ten people died and more than 60 were injured, some seriously. In September, one more person died of injuries, bringing the total to 11.

The supercell storm became so intense at one point that it formed at least two tornados simultaneously. This caught one group of storm chasers off guard. Fortunately, they escaped the deadly vortex by the narrowest of margins.

Damage surveys estimated the tornado's winds topped 205 mph (330 km/h). This meant the Greensburg twister was a rare EF5 tornado, at the top of the scale. Fewer than 1 percent of all reported tornados ever reach EF5, the type that accounts for most tornado deaths.

At least 12 more tornados formed from the same storm after it mowed through Greensburg and tracked northeast. One of these twisters grew even larger, reaching 2 miles (3.2 km) in diameter. Two more people died in the storm, including a police officer trying to warn the town of Macksville, Kansas.

The NWS issued a final tornado warning for the event just after 2 A.M. In all, observers spotted 136 twisters on May 4, with an additional 109 reports of high winds and 429 of large hail.

The following day, another round of severe weather struck the same region bringing 91 tornados and one fatality. My chase activities May 5 nearly ended in disaster. While retreating westward for the evening, I tried to undercut a fast moving tornadic storm in western Oklahoma at night. A forming tornado missed me by less than a mile.

I took the next few days off.

Warren Faidley *is a journalist and storm chaser who specializes in the coverage of severe weather, global warming, and natural disasters. His still photography and storm videos appear frequently in print and broadcast media.*

Is global warming powerful

Rising sea-surface temperatures feed bigger, longer-lived, and more destructive storms.

By Daniel Pendick

The tropical Atlantic Ocean has been in a bad mood recently. Two record-breaking hurricane seasons ravaged the region in 2004 and 2005. The damage in 2004 in the United States alone reached $42 billion, almost enough to buy 10 nuclear-powered aircraft carriers.

Then Katrina happened. The storm made landfall August 28, 2005, with winds of 130 mph (209 km/h).

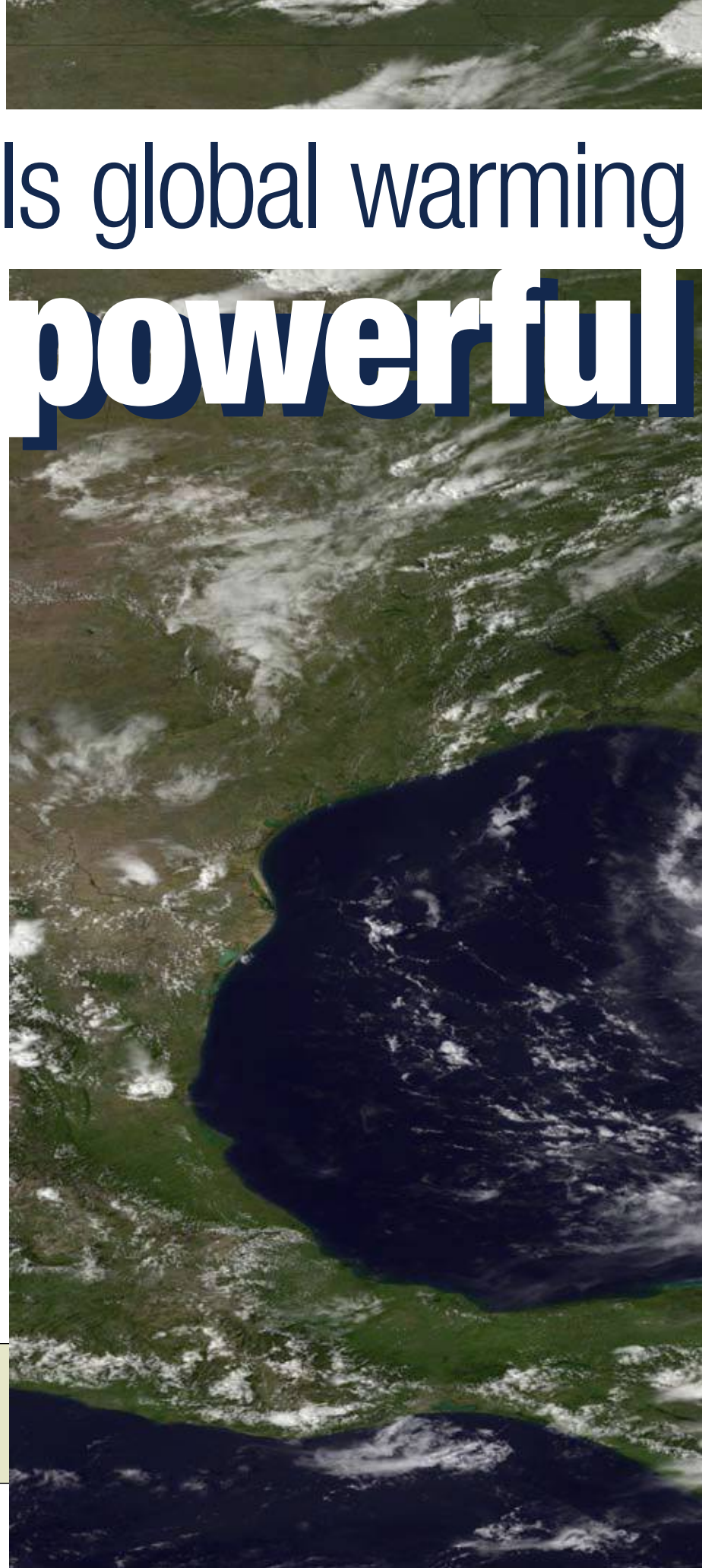
Katrina unleashed a flood tide on New Orleans a dozen feet above normal. When the levees failed, the storm surge submerged 80 percent of the city, killed some 1,300 people, drove hundreds of thousands from their homes, and caused more than $100 billion in damage.

Meanwhile, as Katrina came and went, another storm was brewing — this one in the field of hurricane research. In a cosmic coincidence, three important new hurricane studies appeared on dates close to Katrina. This inspired a lot of media attention on hurricane research.

Two months before the storm, Kevin Trenberth of the National Center for Atmospheric Research (NCAR) presented an analysis of hurricanes and global warming in the journal *Science*. He concluded that human influences likely are increasing the intensity of hurricanes, and causing a shift to more extreme storms.

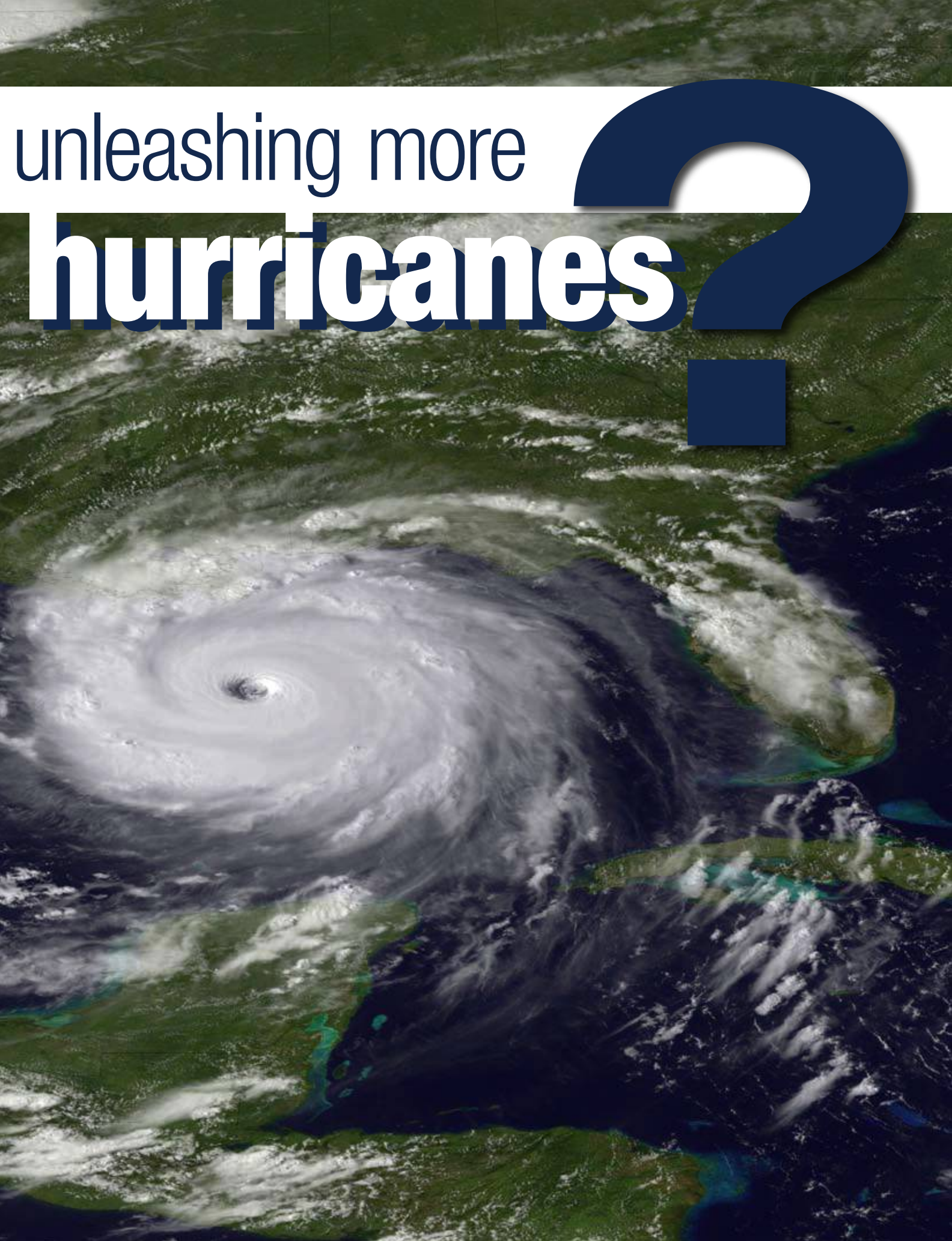
Then, 3 weeks before Katrina, Kerry Emanuel of MIT published a study in the journal *Nature*. He reported statistical evidence that the potential destructiveness of hurricanes has risen significantly since the mid-1970s.

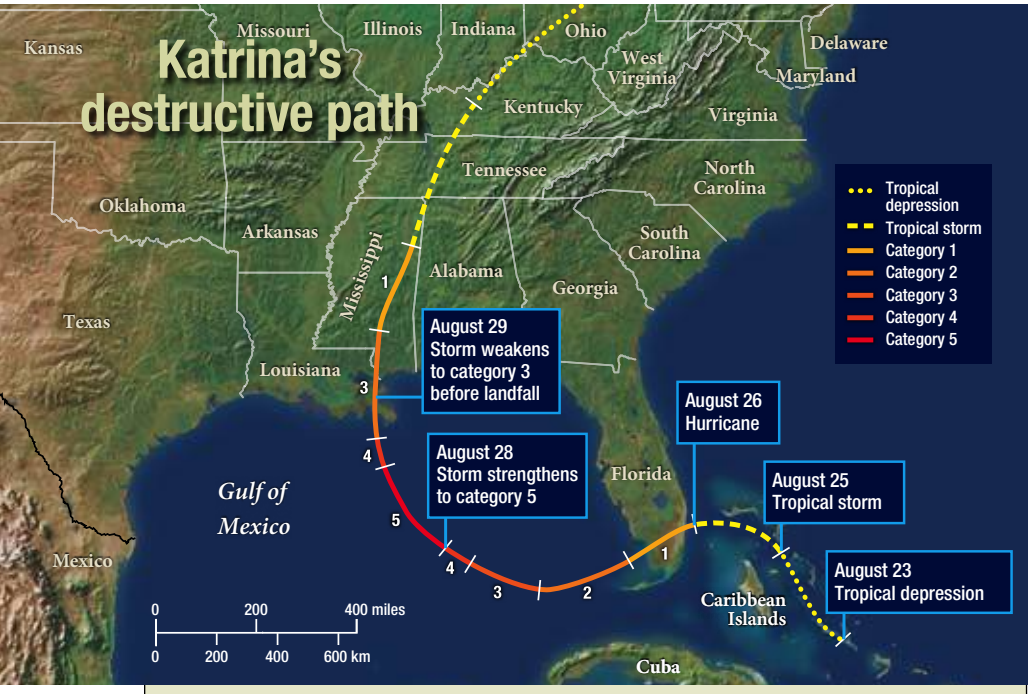
Just 2 weeks after Katrina made landfall, a team from the Georgia Institute of



HURRICANE KATRINA scuds toward New Orleans August 29, 2005. After 2 years of raucous storm seasons, many people fear global warming portends more Katrina-class cyclones. CIMSS/SSEC

unleashing more hurricanes?





KATRINA CROSSED FLORIDA before intensifying over the Gulf of Mexico's warm waters. Winds then steered the storm onto the coast, where it ravaged New Orleans before weakening over land. *EXTREME WEATHER:* ROEN KELLY

HURRICANE Katrina's powerful winds left a trail of destruction in Biloxi, Mississippi. The storm tossed trucks around like toys and scattered heavy rolls of newsprint at this industrial site. NOAA

Technology and NCAR, led by Peter Webster, published another worrisome report in *Science*. The study concluded that "major" hurricanes — the category 4 and 5 storms that cause the most devastation — also have increased significantly.

"And by then, Rita was spinning out in the Gulf," says Georgia Tech's Judith Curry, a member of the team that published the second *Science* paper. "It was just absolutely uncanny."

Rita was the 17th named storm, the fifth major hurricane, and the third category 5 storm of the awesome 2005 season. Added to existing public concern about global warming, the new reports were a recipe for a perfect media storm.

Hurricanes feed off heat, and the sea surface is getting warmer — some 0.9° Fahrenheit (0.5° Celsius) since 1975. In the wake of Katrina and the previous active season, people started asking whether hurricanes were growing more vicious. Is global warming juicing up the Atlantic hurricane machine?

Seeds of destruction

It takes a lot more than just a warm ocean to spawn a hurricane. They develop from atmospheric disturbances that gradually become more organized and powerful, given the right conditions.

Atlantic hurricanes commonly start over Africa. The juxtaposition of hot, dry air from the Sahara and warm, moist air from equatorial jungles creates atmospheric disturbances. Scientists usually refer to these thunderstorm clusters as "easterly waves."

Trade winds blow the disturbances off the coast and over the tropical Atlantic. Most easterly waves simply wither and die. But given favorable conditions, an immature storm can evolve into a revolving system, or vortex — the seed of a tropical hurricane.

Key surface conditions that can turn a seed into a storm include water temperatures over 79° F (26° C), plentiful water vapor, and relatively low pressure. The change in wind speed and direction with altitude, or "wind shear," must not be too great. If the shear is too strong, it may tear the developing vortex apart.

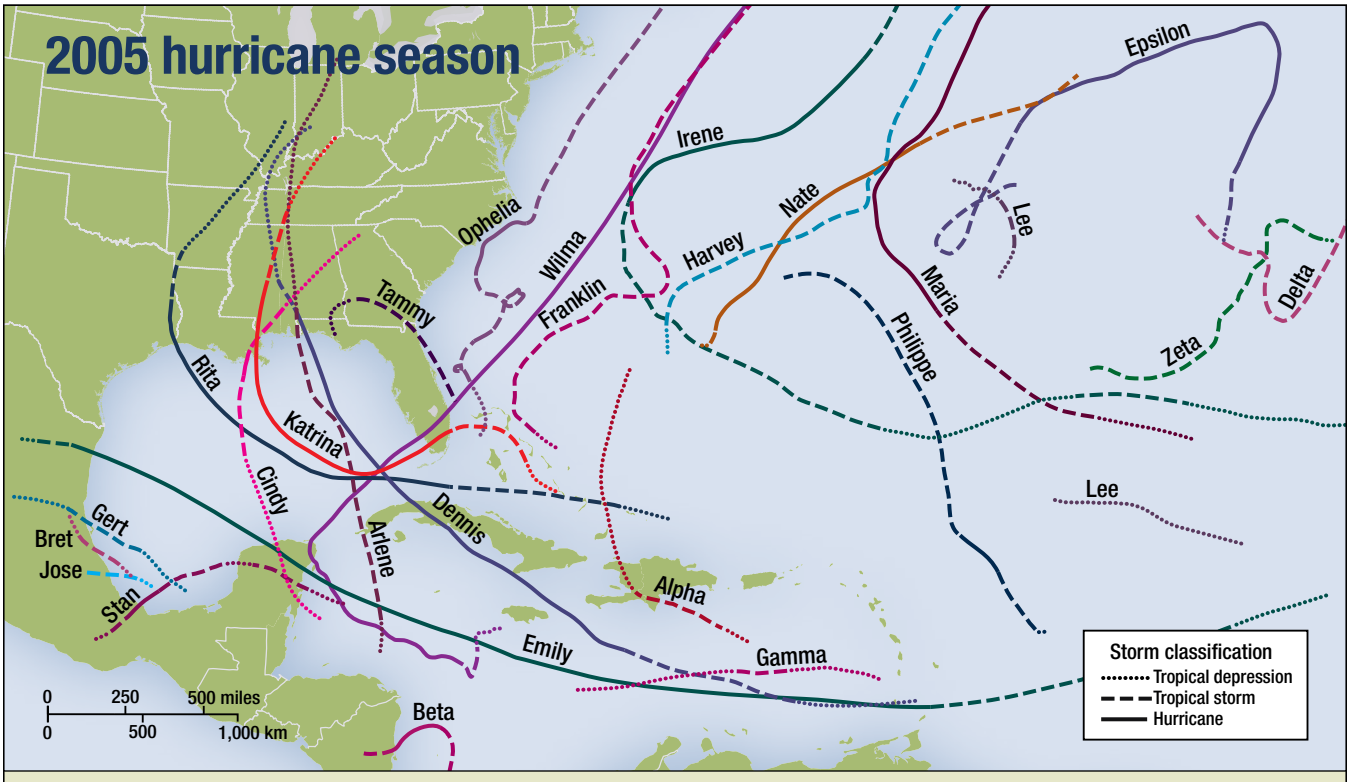
On their way across the Atlantic, seedlings draw energy from the sea. As the air in a seedling warms, it expands and its pressure drops. It also gains spin due to the effects of Earth's rotation. North of the equator, the system begins to spin counterclockwise. A cluster of thunderstorms with central circulation and low pressure is called a tropical depression.

When the central winds reach 40 mph (64 km/h), the system graduates to a named tropical storm. Finally, if the winds hit 74 mph (119 km/h), the tropical storm becomes a category 1 hurricane. With increasing winds and falling central pressure, the storm intensifies. It also develops a defined, central "eye." Hurricanes that top the Saffir-Simpson intensity scale, at category 5, have winds in excess of 155 mph (249 km/h) and a central pressure less than 920 millibars.

By the numbers

Larger-scale processes also influence tropical-storm activity. The famous El Niño is the most important. This semi-periodic warming of the equatorial Pacific Ocean can affect weather and climate at great distances. El Niño perturbs high-altitude wind patterns in such a way that wind shear increases over the Atlantic. This suppresses hurricane formation.

In the winter of 2004–2005, low wind shear and slightly warmer sea-surface temperatures helped fuel two wild hurricane seasons. When an El Niño developed in 2006, it helped suppress North Atlantic hurricane activity. Coincidentally, none



AN ABOVE-AVERAGE TALLY of 15 tropical storms and 9 hurricanes, six of which were major storms, ravaged the North Atlantic in 2004. The following year, which brought the disastrous Katrina, was even more active, with 15 hurricanes. *EXTREME WEATHER:* ROEN KELLY

of the five 2006 hurricanes hit the continental United States. The total number of named storms — nine — was the lowest for any season since 2001.

The coincidental timing of Katrina with three studies linking hurricane activity to global warming had two effects. First, it caused Trenberth's, Emanuel's, and Curry's phones to ring off their hooks. Second, it upped the ante on the climate-change debate. "It was the whole hurricane issue that really woke people up about global warming," Curry says.

On the downside, the furor over Katrina obscured the simple question Trenberth, Curry, and Emanuel had set out to study: When sea-surface temperatures rise, what happens to hurricanes?

To most people, Emanuel says, the assumed answer is: "In a global-warming world, there are more hurricanes, and that is a bad thing." Not surprisingly, reporters often asked him whether more hurricanes will occur in the future. "That is exactly the wrong question," he says.

To understand why, consider another destructive natural hazard — earthquakes. What do seismologists, the specialists who study the causes and consequences of groundshaking, want to know about earthquakes? Among other things, they want to know what triggers earthquakes, how faults store energy, and how tremors affect different kinds of structures.

But the thing seismologists most definitely do not care about is the total number of earthquakes. "You wouldn't go to a conference and hear a seismologist say we had 10,463 earthquakes around the world last year," Emanuel says. "That would be silly. You just cannot put a little tremor that you can't even feel into the same bin with a magnitude 8.0 earthquake."

Similarly, people ask about hurricane frequency because that's the convention weather forecasters established years ago to rate the severity of individual storm seasons. So we count named storms, total number of hurricanes, how many major (category 4 or 5) hurricanes, and — most important of all — the seasonal tally of landfalling hurricanes.

Traditions in science die hard, Emanuel laments. "One of the traditions we have in hurricane science, which I don't think is a particularly good one, is we count hurricanes. And we shouldn't care how many there are. But they're easy to count, especially with satellites."

The power and the fury

Satellites also allow scientists to chart storm duration. With the advent of direct measurement of storm windspeeds and atmospheric pressure from aircraft, along with estimates from satellites, hurricane forecasters can track changes in storm intensity over time. In other words, they can watch as a storm climbs the Saffir-Simpson scale from category 1 to 5.

But if you want to ask what effect global warming is having on hurricane activity, what do you look at — storm frequency, duration, or intensity? Emanuel says none of these alone gives you the full picture. So, he devised a new measure called the power dissipation index, or PDI. It is the total amount of energy hurricanes produce. It's similar to a magnitude scale for earthquakes. PDI depends largely on how much heat is available at the ocean surface — which depends, in part, on global warming.

In 2005, 15 hurricanes — seven of them major — struck the North Atlantic.

CANAL BREACHES flooded large portions of New Orleans because of Katrina. Above, ramps on Interstate 10 at West End Boulevard rise from floodwaters. U.S. COAST GUARD/KYLE NIEMI

EXTENSIVE FLOODING of neighborhoods east of the 17th Street Canal (left center, oriented north-south) is evident in this image acquired September 8, 2005, from the International Space Station. Areas inundated by Katrina are dark greenish-brown. NASA

Emanuel sees hurricanes through the eyes of a physicist, not a forecaster. He explains that hurricanes are "heat engines" that convert heat energy into mechanical energy. The more heat the storm takes in, the faster its winds blow and the lower its central pressure falls. The mechanical energy of the storm — its damaging winds — causes most of the mayhem, either directly or by piling up water near the shore into a storm surge.

The number of hurricanes per season, Emanuel points out, is just one contributor to the total destructive potential of the storm season. "It's a secondary issue whether that comes about because of more hurricanes, more intense hurricanes, or longer-lived storms."

Emanuel titled his short report in *Nature*, "Increasing destructiveness of tropical cyclones over the past 30 years." He limited the study to areas for which we have good aircraft observations and measurements since 1975 — the North Atlantic and the western North Pacific.

In Emanuel's equation for PDI, potential destructiveness rises with storm frequency, intensity (category), and duration. He tallied the power dissipated over the entire storm track and total lifetime. It's analogous to asking how much gas a car's engine burns in its journey across land. The total gas consumed is related directly to the mechanical work the car did with the fuel.

Similarly, the amount of fuel available to a storm determines how much "work" it can do. In this case, the heat stored in warm sea-surface water supplies the fuel. When the available energy is higher — because of global warming — the destructiveness of hurricanes rises.

Emanuel found that the destructive potential of hurricanes in the North Atlantic and western North Pacific has more than doubled since 1975. As for global warming's role on the equation, Emanuel wrote, "The upturn in tropical mean surface temperatures since 1975 has been generally ascribed to global warming, suggesting that the upward trend in tropical cyclone PDI values is at least partially anthropogenic."

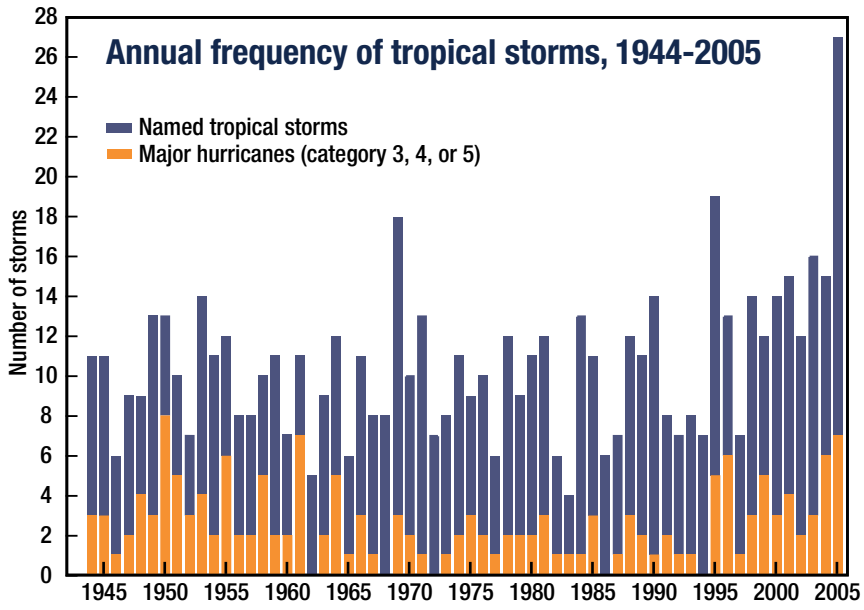
Global storm upturn

The Georgia Tech and NCAR study led by Webster and Curry looked at some of the same storm data as Emanuel. But instead of total power dissipated, they focused on changes in the number of major hurricanes across the globe, not just in the North Atlantic and North Pacific.

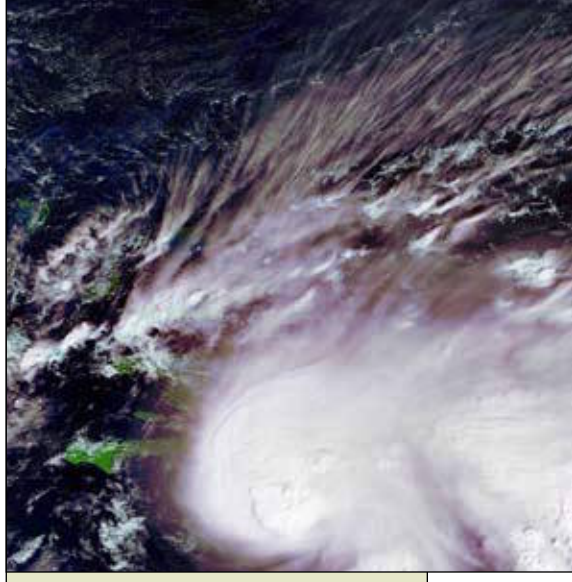
To do so, they relied on all the tropical-storm and hurricane data collected by satellites from 1970 to 2004. This is the only global data collection available. Before 1945, countries kept statistics only on landfalling hurricanes — the ones they could see. From 1945 to 1970, observations of storms at sea were limited to the North Atlantic and North Pacific. Only in 1970 did we gain the ability to monitor storm activity in entire ocean basins.

The Georgia Tech team counted the number of hurricanes, the estimated intensity of the storms, and the number of days the storms lasted. The bottom line: The number of major hurricanes globally has doubled since 1970.

But this comes with a caveat. The data on global hurricane activity have important limits. One, satellites can't measure storm intensity directly. It requires a cal-



RESEARCH BY MIT scientist Kerry Emanuel finds that the energy hurricanes dissipate each year is rising with global warming, although not necessarily because there are more storms. Hurricane frequency depends on more than warmer ocean temperatures. *EXTREME WEATHER:* ROEN KELLY



THE ENVISAT SATELLITE snapped this image of a tropical depression strengthening across the Caribbean Sea. At this moment, the storm was merely a cluster of thunderstorms with circular winds and a low central pressure. When the system's winds reached 40 mph (64 km/h), it became a tropical storm and was named Noel. ESA

culation based on some assumptions. And the measurement is partly subjective: It is based on an individual's interpretation of satellite data versus standard instruments on research aircraft.

Overall, the data are spotty. Most satellite observations come from the Geostationary Operational Environmental Satellites (GOES), which can hover in one spot above entire ocean basins. Some data come from satellites used in forecasting. Europe and Asia have equivalent systems. The longest-term and best statistics come from the North Atlantic, so most research has focused on that basin.

But Curry warns it would be a mistake to come to conclusions about hurricanes and climate by looking only at the North Atlantic. Atlantic hurricanes comprise just 11 percent of global cyclones. Landfalling hurricanes there are even less significant: only 1 percent of the total.

That means even if Atlantic hurricanes showed a dramatic upturn in activity, it wouldn't tell us about the ultimate effect of global warming. Looking only at the North Atlantic, Curry says, "is like polling California to see how popular a presidential candidate is."

To reach a conclusion, scientists need more data. "As far as the global hurricane intensity data, I don't know if that's ever going to be sorted out until we have some aircraft measurements in other basins. The global intensity data are not of high enough quality to convince everybody."

Hurricanes in a warming world

Given the evidence that hurricane activity is increasing, what can we conclude about the bigger question? In a world headed toward a certain doubling of atmospheric carbon dioxide, what will happen to hurricane activity?

One thing we can be sure of: If sea-surface temperatures continue to rise, so will hurricane intensities. "Nobody disagrees that if you increase the sea-surface temperatures you are going to, on average, increase the intensity," Curry says. "The question is how much, and are the data good enough to identify this increase outside of the North Atlantic?"

With the recent statistical studies by Emanuel, Curry's group, and several other teams, she says, "All the simple stuff has been done. Now we're at the hard part where we have to really dig in and use more theory and modeling." The trouble is, the climate models and the data don't match, and the reason isn't entirely clear.

Some researchers look to computer climate models for more evidence, but this is fraught with uncertainties. In a recent study, Trenberth looked at hurricane precipitation and the flooding that

Saffir-Simpson Hurricane Scale

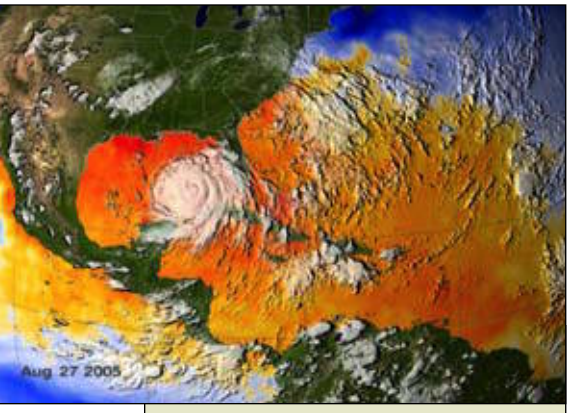
Category	Pressure mb	Winds mph	Surge feet
Depression	—	< 39	—
T. Storm	—	39–73	—
Hurricane 1	> 980	74–95	4–5
Hurricane 2	965–980	96–110	6–8
Hurricane 3	945–965	111–130	9–12
Hurricane 4	920–945	131–155	13–18
Hurricane 5	< 920	>155	>18

THE SAFFIR-SIMPSON SCALE rates hurricane intensity based on maximum wind speed, how high the storm mounds up the ocean at the coast (storm surge), and the minimum atmospheric pressure in the storm's core, or "eye."

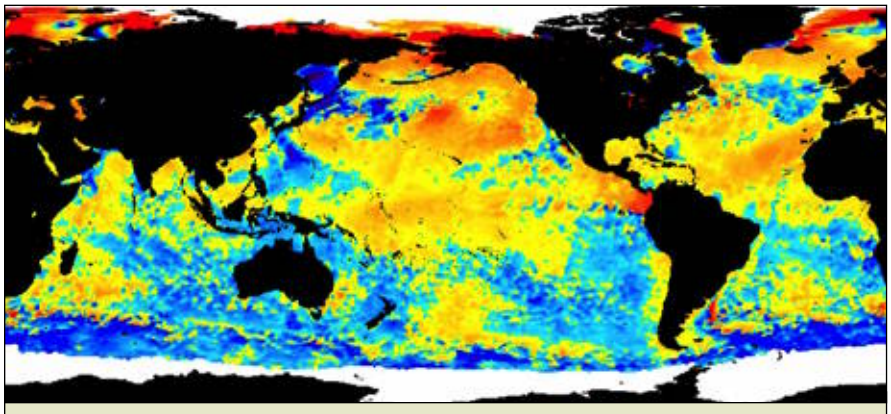
results. He determined that rainfall has increased 6 to 8 percent in tropical storms as a consequence of global warming and higher sea temperatures.

The *Science* study led by the Georgia Tech group suggests that for each 1.8° F (1° C) rise in sea-surface temperature, hurricane intensity rises 6 percent. On the other hand, a handful of climate models that include hurricane simulations come up with a 2-percent rise in storm intensity.

Which do we believe? "So you've got a range of 2 to 6 percent, and I would



WARM OCEAN WATERS fuel hurricanes. This enabled Katrina to gain strength after it crossed over Florida and moved into the Gulf of Mexico. This image depicts a 3-day average of actual sea-surface temperatures for the Caribbean Sea and the Atlantic Ocean, from August 25–27, 2005. Areas in yellow, orange, or red are 82° F (28° C) or warmer. NASA/SVS



SCIENTISTS ANNOUNCED THE RETURN of El Niño in September 2004 with this satellite image of warmer-than-normal sea-surface temperatures (yellow, orange, and red) in the central and western equatorial Pacific. In 2006, stronger El Niño conditions suppressed tropical storm activity in the Atlantic following the devastating hurricane seasons of 2004–2005. NOAA

argue that the climate models almost certainly underestimate it, and we probably overestimate it," Curry says. Her best guess: We'll see a 3- to 5-percent rise in . storm intensity for every degree Celsius rise in sea-surface temperature. She puts her hope in better models as well as better data in the future. "High-resolution climate models coupled to the ocean will tell us a lot, too, about what we might expect. Progress is going to be more slow in coming, but it's going to be deeper and more fundamental progress."

At the moment, the main problem in predicting the response of hurricane activity to global warming is the limited resolution of climate models: The models don't really "see" details as fine as hurricanes. The smallest features they can resolve are hundreds of miles wide.

"The models produce these big sloppy things that don't have nearly the wind speed they should have," Emanuel says. "That doesn't stop people from saying there's more of them, or fewer of them, or they're a little bit stronger or weaker. But they are so poorly resolved that, from my point of view, it's at best weak evidence about what will happen in the future."

The stormy crystal ball

Perhaps in reaction to all the hyperbole over Katrina, Emanuel is adamant about limiting his predictions for the global-warming world to only what he can support scientifically. And right now, that doesn't go very far.

Will there be a larger number of hurricanes? In the North Atlantic, it's possible. Since the 1970s, the higher frequency of hurricanes in the Atlantic basin accounts for most of the rise in PDI. But in the Pacific, the increase in hurricane intensity and duration explains almost all the rise in the PDI. Emanuel says no physical theory can yet account for these trends. It remains a black box.

However, a theoretical foundation exists for associating sea-surface temperature and storm intensity. More precisely defined, it is the "potential intensity" that rises. The PI is simply the upper limit on how strong a storm's winds can blow under ideal conditions.

The hotter the ocean surface, and the colder the high atmosphere, the more intense a storm can become — up to the physical limits imposed by friction and air density. The speed at which water evaporates from the sea surface also plays a role. The evaporation rate depends on ocean temperature and other factors.

Those "other factors" account for part of the uncertainty in predicting hurricane destructiveness in a warmer climate. A single massive volcanic eruption like that of Mount Pinatubo (the Philippines, June 1991) could reduce hurricane activity for several years. The aerosol particles an eruption spews out block sunlight and reduce surface temperatures. From 1918 to 1960, hurricane activity may have been greater, in part, because of the lack of a major volcanic eruption.

Then, from the 1950s to 1980s, sulfate aerosol pollution — from burning fossil fuels, for example — spiked in the industrial world. That change helped dampen hurricane activity. Since the 1980s, global warming (and anti-pollution technology) has helped juice up the global hurricane machine again.

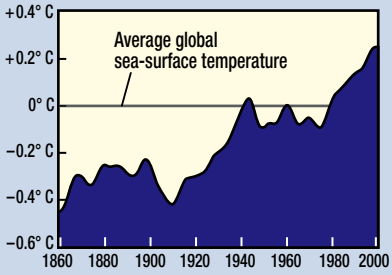
Most importantly — and perhaps most frustratingly — Emanuel's equations cannot, and never will, answer the questions that launched the post-Katrina furor over climate change and hurricanes: Did global warming cause Katrina? Will there be more Katrinas in the future? Answers: No, and nobody knows.

"Hurricanes are statistical creatures," Emanuel says. "They are part of a chaotic system. You can't really say much about individual storms at all." We should not look at any storm individually. It would be like studying an elephant by examining only the trunk, tail, or feet.

On average, however, we should expect a modest increase in storm intensity. "We don't have a theory to guide us on duration and frequency. All we can say is, based on the observations, that hurricane power and sea-surface temperature are so well correlated," Emanuel says.

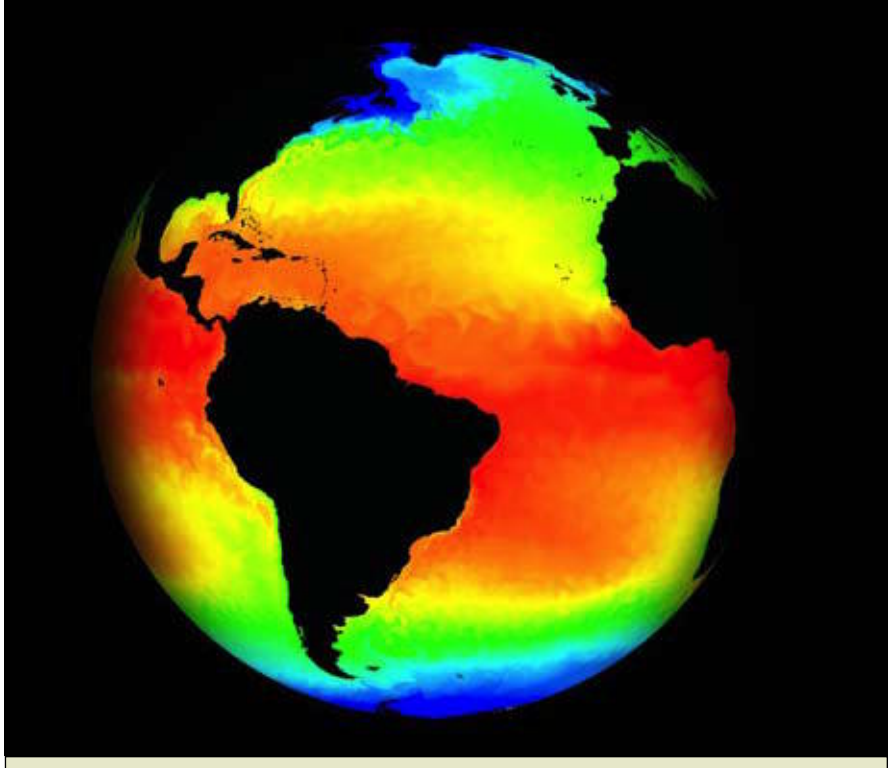
Know the enemy

In the broader societal perspective of natural hazards and their mitigation, hurricane intensity, frequency, and duration mean little to society as long as the storm doesn't hit land. "Do people really care if there were 15 storms in the Atlantic last year if none of them hit land?" Emanuel asks.



SEA-SURFACE TEMPERATURES have risen during the past century. This warming trend may contribute to more intense, frequent, and long-lasting hurricanes in some parts of the world.

EXTREME WEATHER: ROEN KELLY, AFTER IPCC



IN A GLOBAL-WARMING FUTURE, sea-surface temperatures will continue to rise. Many scientists think this will increase hurricane intensity, frequency, and duration, depending on the location, year, and other factors. NASA

Perhaps a little bit, because the more hurricanes that occur, the greater the chance one could wander over to the coast. But right now, Emanuel says, climate data cannot predict whether landfall will be more likely. "So you can't even ask the question. It's a crap shoot unless you look at it as a pattern over 100 years or more."

Ultimately, Emanuel and his fellow hurricane scientists hope more sophisticated modeling, better data, and improvements in theory will lead to practical benefits. "We do want to improve forecasts and we do want to know whether there are going to be any more Katrinas," Emanuel says.

Also, he and his colleagues are beginning to think that hurricanes are a strong feedback in the climate system. Storms remove vast amounts of heat from the ocean surface, and they stir and mix the ocean to depths of hundreds of feet. Climate models, the scientists believe, should include these processes.

As for science saving lives and preventing storm devastation, Emanuel points the finger of responsibility elsewhere. "All of us feel the immediate problem is policies that promote Katrina-like disasters. Regardless of whether the climate is changing, that needs immediate and critical attention."

Daniel Pendick *is an associate editor of* Astronomy *magazine and a freelance writer who has written widely on hurricanes and other natural hazards. In 1996, he flew through Hurricane Madeline with the National Oceanographic and Atmospheric Administration "hurricane hunters."*

After the Katrina disaster, Emanuel, Curry, and eight other prominent scientists signed a policy paper, "Statement on the U.S. Hurricane Problem." The document concluded:

> We are optimistic that continued research will eventually resolve much of the current controversy over the effect of climate change on hurricanes. But the more urgent problem of our lemming-like march to the sea requires immediate and sustained attention. We call upon leaders of government and industry to undertake a comprehensive evaluation of building practices, and insurance, land use, and disaster relief policies that currently serve to promote an ever-increasing vulnerability to hurricanes.

Coastal conundrum

The "lemming-like march to the sea" in the letter refers to the accelerating development along the U.S. coastline. Coastal regions comprise only 17 percent of the country's land area but hosts more than half its population. As of 2003, about 153 million people (53 percent of the population) lived in 673 coastal counties — an increase of 33 million since 1980.

Part of what drives coastal development, Emanuel and many other experts agree, is policies that make inland citizens subsidize low insurance rates for coastal residents. In effect, the inland population pays higher rates than they really should to keep rates lower in more risky areas. Federal flood-insurance rates also do not reflect the actual risk of coastal hazard zones. Federal disaster relief is quick, plentiful, and, frankly, expected after a killer storm. Just ask President George W. Bush and the former director of FEMA.

When insurance rates go up after storms to better reflect the actual financial risk to insurers, the more affluent stay, and the less affluent have to leave.

153 million people live on the U.S. coast. Many live in hurricane hazard zones.

Coastal residents typically exert pressure on their leaders to keep the status quo, although it is irrational and unfair, Emanuel says. "We subsidize the rich on the shore at the cost of the poor. We keep rates down at the coast, and inland people are paying for it."

Hurricanes, however, don't discriminate. All coastal residents, rich and poor, may face nature's wrath on an even greater scale in a global-warming future. And perhaps more troubling, how many $100 billion storms can even a rich nation like the United States tolerate?

Taking the planet's temperature

The highs and lows of known record-setting temperatures span some 265° Fahrenheit (147° Celsius).

By Laura Baird

While the hottest temperature on record occurs, somewhat predictably, near the equator (in Libya), and the coldest near a pole (in Antarctica), latitude alone cannot account for these extremes.

A high Sun, cloud-free skies, and stalled weather systems each can contribute to warm days. Solar rays heating sand and rock, which trap heat, also plays a part. Thus, Africa's Sahara Desert, California's Death Valley, and east-central Australia most often experience temperatures greater than 120° F (49° C). In the case of El Azizia, Libya's record-breaking day, the heat had built for 2 days before cresting at 136° F (58° C) September 13, 1922.

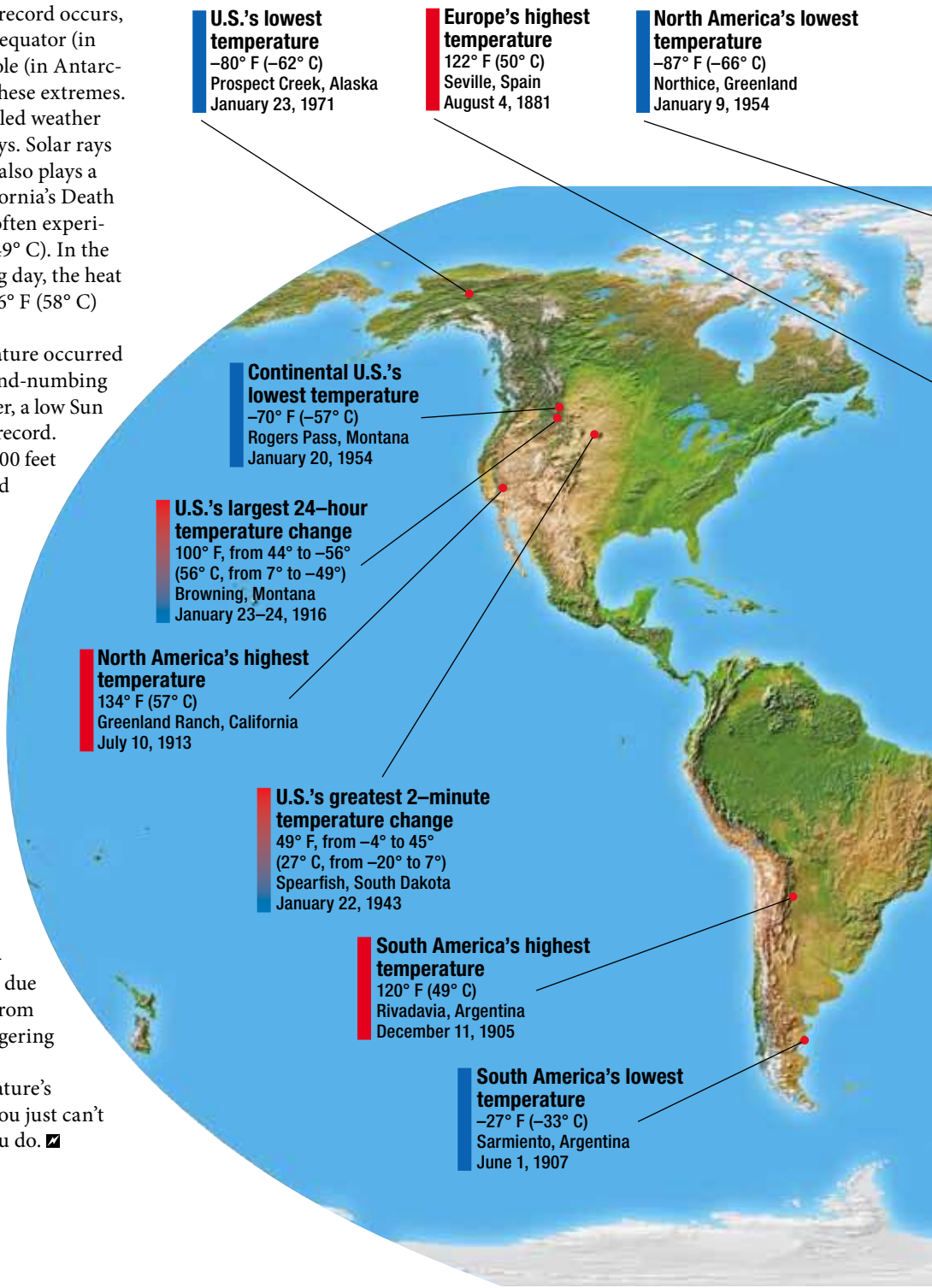
The world's coldest recorded temperature occurred in Vostok, Antarctica, where it was a mind-numbing –129° F (–89° C) July 21, 1983. Snow cover, a low Sun angle, and dry air all contributed to this record. Vostok also stands at an elevation of 12,000 feet (3,700 meters), which makes it higher, and thus colder, than the nearby South Pole.

In the Northern Hemisphere, Siberia has the lowest temperatures. The North Pole, surrounded by ice floes in relatively balmy seawater, rarely dips below –40° F (–40° C).

While temperatures in some places are reasonably predictable, Browning, Montana, saw the mercury plummet an astounding 100° F (56° C) between January 23 and 24, 1916. An Arctic front dropped temperatures from 44° F (7° C) to –56° F (–49° C) overnight.

Stranger still, Spearfish, South Dakota, experienced both winter and spring the morning of January 22, 1943. In only 2 minutes, the temperature rose from –4° F (–20° C) to 45° F (7° C). Temperatures fluctuated throughout the day due to chinook winds that mixed warm air from over the Black Hills with a cold front lingering at the mountains' base.

Such a dramatic change showcases nature's unpredictability at its best. Sometimes you just can't dress for the weather, no matter what you do.

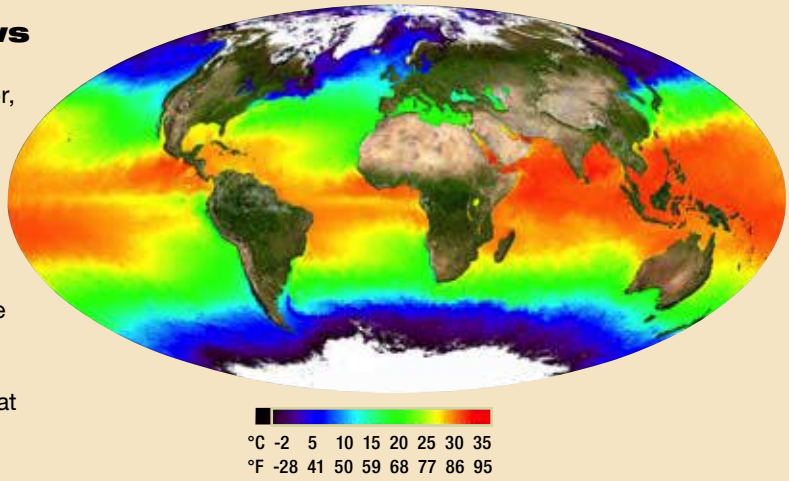


Where the warmest water flows

Latitude largely dictates the surface warmth of Earth's oceans. The Sun heats water at the equator, and the temperatures decrease toward the planet's frozen poles.

This satellite image of water temperatures roughly 3 feet (1 meter) below the surface was taken during May 2001. It shows the Indian Ocean harbors the warmest water, topping out near 95° F (35° C). The average ocean surface temperature is around 63° F (17° C). While sunny beaches attract tourists, warm water also feeds the fiercest storms. Tropical cyclones require a sea-surface temperature at least 80° F (27° C) to develop. — *L. B.*

JACQUES DESCLOITRES, MODIS LAND RAPID RESPONSE TEAM, NASA/GSFC



World's greatest difference between recorded low and high temperatures
184° F, between –90° and 94°
(102° C, from 34° to –68°)
Verkhoyansk, Russia

Asia's lowest temperature (tie)
–90° F (–68° C)
Oimekon, Russia
February 6, 1892
Verkhoyansk, Russia
February 7, 1892

Europe's lowest temperature
–73° F (–58° C)
Ust'Shchugor, Russia
December 31, 1978

Asia's highest temperature
129° F (54° C)
Tirat Zevi, Israel
June 21, 1942

Africa's lowest temperature
–11° F (–24° C)
Ifrane, Morocco
February 11, 1935

Australia's highest temperature
128° F (53° C)
Cloncurry, Queensland
January 16, 1889

World's highest temperature
136° F (58° C)
El Azizia, Libya
September 13, 1922

Australia's lowest temperature
–9° F (–23° C)
Charlotte Pass,
New South Wales
June 29, 1944

Antarctica's highest temperature
59° F (15° C)
Vanda Station
January 5, 1974

South Pole's highest temperature
8° F (–13° C)
December 27, 1978

World's lowest temperature
–129° F (–89° C)
Vostok, Antarctica
July 21, 1983

KEY

- RECORD HIGH TEMPERATURES
- RECORD TEMPERATURE CHANGE
- RECORD LOW TEMPERATURES

NASA EARTH OBSERVATORY/FRANCIS REDDY/*EXTREME WEATHER:* JAY SMITH

Can we live with

Destructive hurricanes, severe droughts, and rising sea levels are just some of the problems our planet will face 50 years from now.

By Robert Henson

FIRE? An increase in greenhouse gases, fueled by human civilization, seems to be tipping the scales in favor of a warming climate. SIMON COLLINS

In the 16th century, some of the greatest Renaissance artists produced vivid images of good and evil: the faithful on one side, sunlit and beaming, and the damned on the other, trapped in fiery pits. If masters like Signorelli were around today, they might find themselves using brush and paint to portray the debates swirling around climate change.

For dyed-in-the-green activists, the choice is clear — it's either a bright new world of bikes and hybrid cars, spinning windmills, and gleaming solar panels, or a hellish scenario of drowning coastlines, toasted croplands, and starving masses. If you're skeptical about human-produced climate change, then you might be seeing another pair of possible futures: a dismal, choiceless economy led by an army of gray bureaucrats, or a Jetsons–style land of tomorrow with everything faster, bigger, and better — all amid a convenient cooldown brought about by natural cycles.

If you encounter anything like these cartoonish scenes in what you're reading and hearing about climate change, it's a sign of just how politicized this mother of all environmental issues can be. True, some common ground has appeared over the last several years. Virtually everyone now agrees Earth is warming and that human-produced greenhouse gases play some role. And it's hard to argue too much against the virtues of basic energy efficiency. But we'll have to do more than change a few lightbulbs to cope with the atmospheric changes that are coming down the pike. Meanwhile, we've also got to take a stab at averting the more drastic potential effects of climate change.

The story so far

Up to now, the changes on a global scale haven't been cataclysmic. Take these two statistics from the 2007 report

climate change?

ICE? Thirty years ago, scientists seriously discussed the possibility of global cooling, which might have made all of Earth resemble Antarctica. GUILLAUME DARGAUD

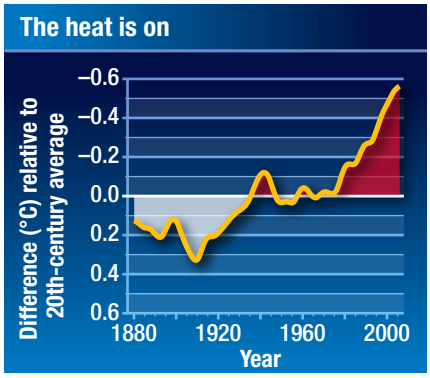
of the Nobel Prize–winning Intergovernmental Panel on Climate Change (IPCC): Earth's atmosphere has warmed a little more than 1.3° Fahrenheit (0.7° Celsius) in the last century; and average sea level has risen about 7 inches (17 centimeters) in the same period.

So far, so good — but averages aren't the most relevant thing to most of us. As noted by Mark Twain, Robert Heinlein, and others, "Climate is what we expect; weather is what we get." One degree Fahrenheit spread over weeks, months, or years doesn't seem like much, but this globally averaged value obscures bigger changes that unfold in certain regions and at certain times.

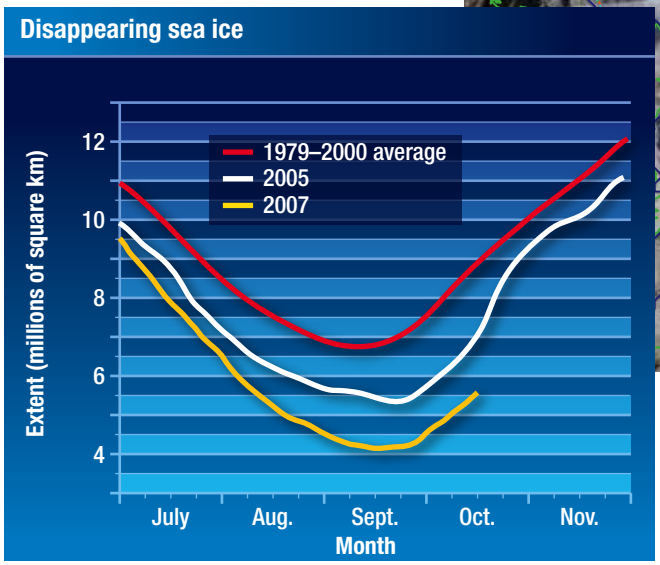
For example, temperatures in the far north are rising much more quickly than in the tropics, thanks to a vicious climatic cycle. Ice reflects more than 80 percent of the sunlight that hits it, but open water absorbs more than 80 percent. So, when sea ice melts, it allows the ocean to gain heat and fosters further melting. In the summer of 2007, unusually ample sunshine and persistent west winds teamed up with long-term warming to carve out a gigantic zone of open water across the western Arctic, stretching from Alaska and Russia almost to the North Pole. More than a third of the Arctic's typical September complement of sea ice vanished, leaving a void big enough to hold both Alaska and Texas.

This was a classic example of how a natural variation (sunshine and steady wind) packs extra punch when it comes on top of the slow burn of climate change. Experts such as Mark Serreze of the U.S. National Snow and Ice Data Center once believed the Arctic wouldn't see an ice-free summer till after 2100. Now, he says, "It could be as early as 2030." Others peg the date as soon as 2013. The most publicized of the melt's potential victims are polar bears, who use near-shore ice as a platform to hunt seals. However, the loss of sea ice also puts other ecosystems at risk, as well as the traditional livelihoods of Inuit residents, who use the ice for hunting, fishing, and transportation.

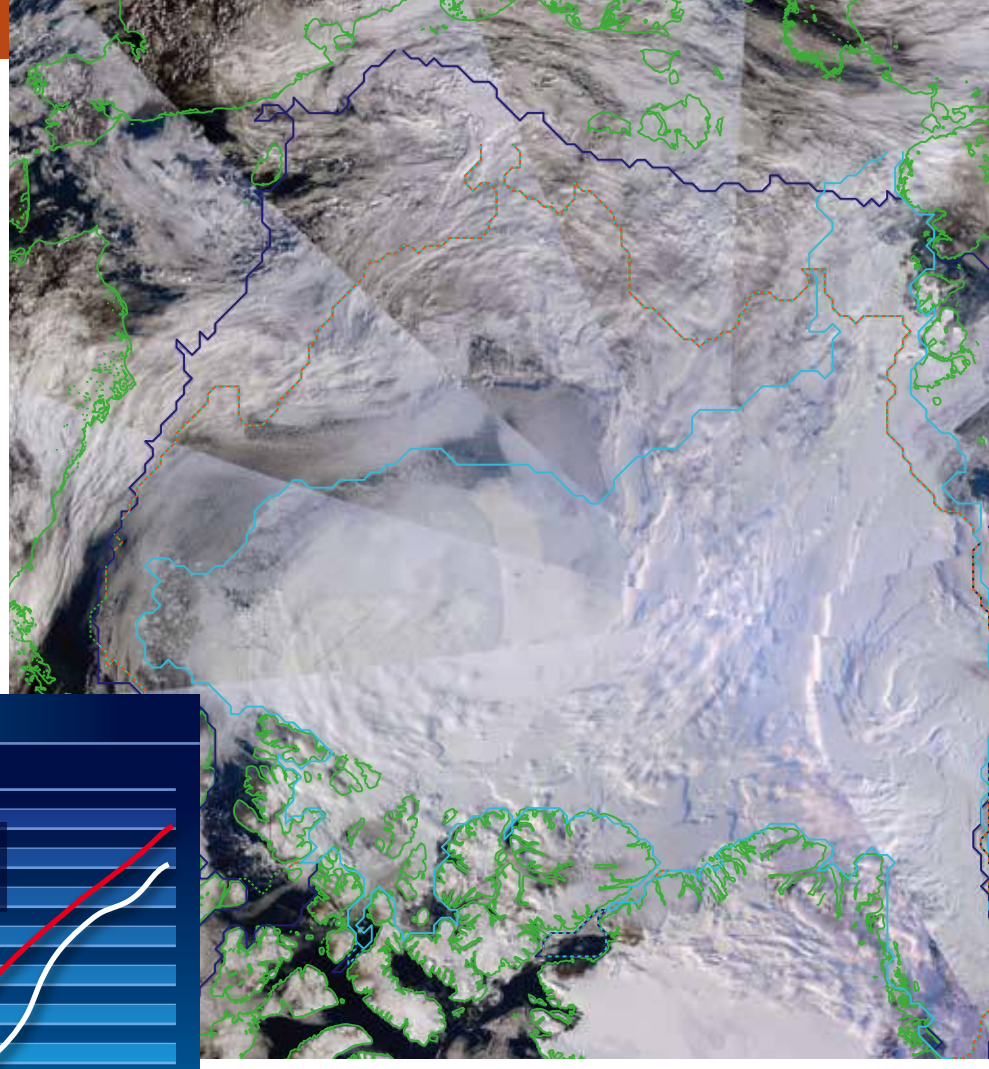
Most people won't be threatened directly by a future Arctic whose ice vanishes each summer, although the open water could produce climatic side effects yet to be analyzed. Because the ice is already floating, its loss won't raise sea



HIGHER TEMPERATURES began to show up in earnest in the late 1970s. This plot shows average annual temperatures over both land and seas compared with the 20th-century average. We're now about 1.3° F (0.7° C) warmer than that average. *EXTREME WEATHER:* RICK JOHNSON, AFTER NCDC/NESDIS/NOAA



SEA ICE IN 2007 fell 30-percent below the average from 1979 to 2000, and significantly below the previous record year (2005). On September 16, 2007, the thinning arctic ice covered just 1.59 million square miles (4.13 million square km). *EXTREME WEATHER:* RICK JOHNSON, AFTER NSIDC



ARCTIC SEA ICE reached an all-time low in September 2007. Despite some clouds, the ice's edge (turquoise line) shows up in many regions, as does the Northwest Passage's open waters (lower left). Green lines show land masses, and the purple line reveals the average sea-ice extent. NSIDC

levels. If anything, global commerce could benefit from new shipping lanes, expanded tourism, and the oil and gas riches that the opened waters may expose.

But rising temperatures elsewhere stand to affect millions of lives, especially through heat waves. An unprecedented round of heat baked western Europe in 2003. England saw its first 100° F (38° C) in more than 300 years of record-keeping. According to various national institutes of health, the onslaught killed at least 50,000 Europeans. Still, it took weeks for officials and the media to realize just what had happened. "Because heat waves don't produce property damage, they don't get the same kind of coverage as other disasters," says New York University sociologist Eric Klinenberg, who analyzed the 1995 heat wave that killed more than 700 in Chicago.

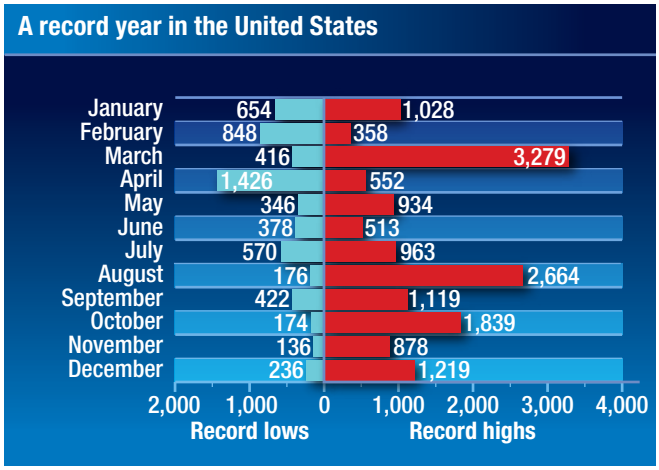
Although many who died in 2003's European tragedy were elderly, research shows most such heat-wave victims otherwise would have lived months or years longer. Poorer and older residents also suffered disproportionately at the hand of a quick but brutal heat spell in 2006 that killed more than 100 in California.

Peter Stott of the UK Met Office Hadley Centre and Martin Hoerling of the National Oceanic and Atmospheric Administration (NOAA) led teams that modeled how heat waves evolve with and without human-produced greenhouse gases. They found that we've made heat waves like the ones in Europe and California several times more likely than they'd otherwise be.

Ironically, most Americans in the Sun Belt states can endure even the most diabolical heat with the help of air conditioning. But tens of millions of others who lack air conditioning are easy prey, especially in the concrete "heat islands" that make up older cities such as Chicago and Philadelphia — not to mention Paris and Brussels. Millions more are at risk across heat-prone parts of Asia.

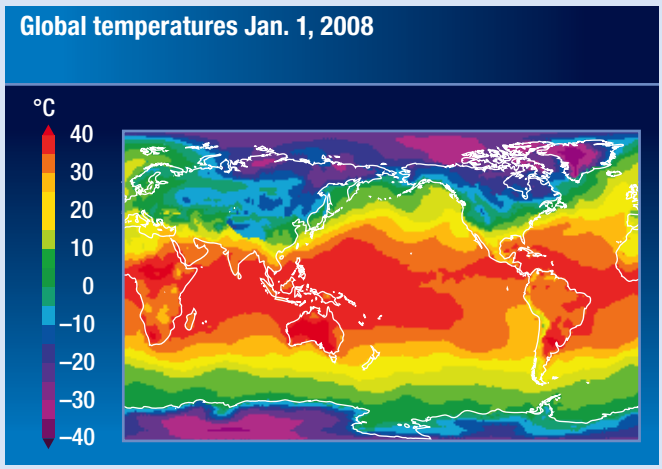
There's also an upside. As you might expect, the death tally related to wintertime cold spells likely will drop. In England, where millions suffer through winter in chilly, drafty homes, a 2001 analysis by Gavin Donaldson of Queen Mary and Westfield College and his colleagues crunched the numbers: They found that by 2050, some 20,000 fewer deaths from cold might occur,

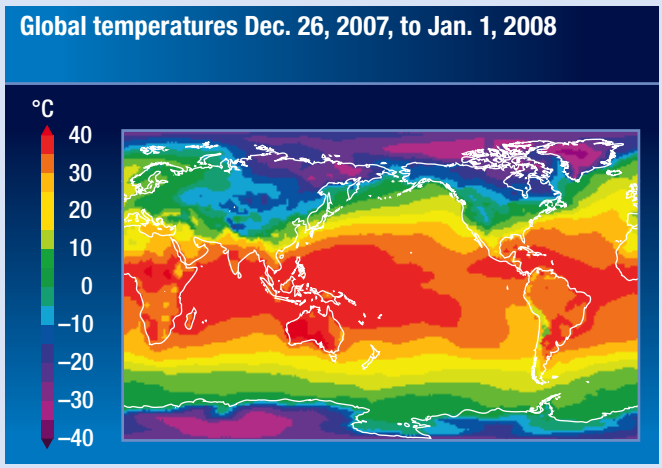
Record highs and lows in 2007

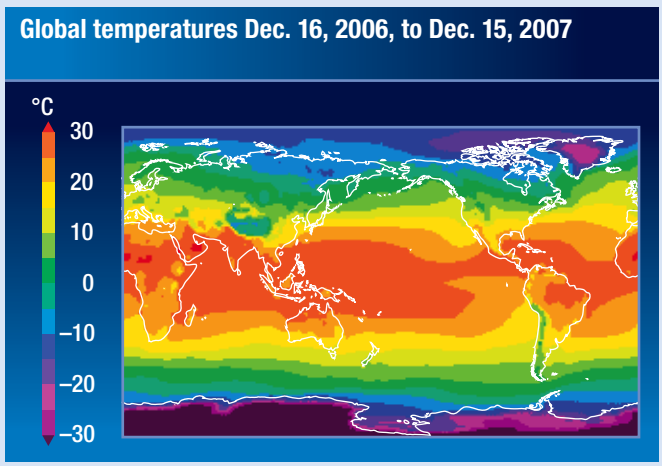


THE MERCURY ROSE to far more record highs than it dipped to record lows in the United States in 2007. Reporting stations saw more record lows only in February and April. *EXTREME WEATHER:* RICK JOHNSON, AFTER NOAA

A warming climate







TEMPERATURES on any given day show significant areas that are colder than normal. These frosty regions tend to average out when you examine weekly or yearly periods, however — a sign that all of Earth may be warming slowly. *EXTREME WEATHER:* RICK JOHNSON, AFTER NOAA/ESRL — PHYSICAL SCIENCES DIVISION

next to only about 2,000 added deaths from heat. Scientists know much less about how already-hot tropical areas might fare, so it's hard to tell whether the drop in cold-related deaths will outweigh the number of heat-induced fatalities globally.

What makes heat and cold waves deadly isn't just their intensity but their unexpectedness — how far they depart from what people can dress for and what their communities are built for. As the 2007 IPCC report noted, more research is needed on how hot and cold spikes will affect human health in a warming world.

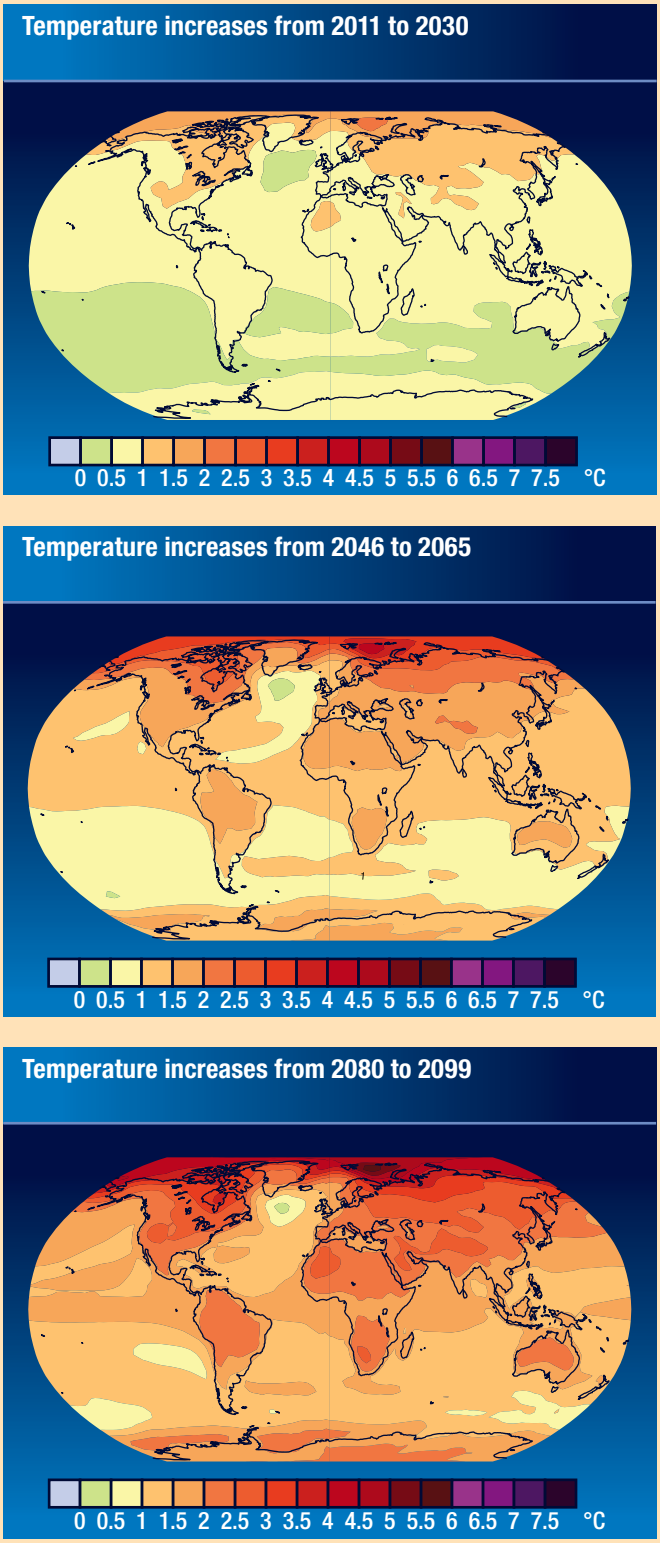
Moister yet drier

One of the cruelest ironies of climate change is that it appears likely to boost drought even as it packs the air with more storm-fueling moisture. The reason is pure physics: Air's ability to "hold" moisture increases dramatically with temperature. On a 70° F (21° C) day with fog (that is, with the relative humidity at 100 percent), there's twice as much water vapor as there is in a 50° F (10° C) fog. Thus, as the world warms, more moisture can enter the atmosphere — roughly 7 percent more for each degree Celsius, according to the IPCC — and where it rains or snows, it's likely to precipitate more intensely on average. But where drought dominates, more moisture will be drawn out of the soil and from the reservoirs that supply water to residents and farms.

In the past several years, climate modelers have closed in on an overall picture of where rain and snow should increase or decrease as this century unfolds. A range of models employed for the 2007 IPCC report shows precipitation will likely increase north of about 40° to 50° north latitude, largely during the winter months. Meanwhile, precipitation should decrease in the subtropics and much of the tropics, except for some monsoon-prone areas that stand to get even wetter. The subtropical drying is especially bad news for the U.S. Sun Belt, where cities from Los Angeles to Atlanta grappled with historic drought in 2007.

Because of increased evaporation, a warmer climate exacerbates the pain of any given drought. Population doesn't help matters. Cities around the world are discovering this the

A hotter climate



TEMPERATURES WILL WARM this century under every scenario considered by the International Panel on Climate Change. Even the model with the least warming, shown here, predicts temperatures several degrees warmer by the 21st century's end. *EXTREME WEATHER:* RICK JOHNSON, AFTER IPCC

DEVASTATING TORNADOS haven't increased with global warming. Climatologists think the conditions that spawn deadly tornados won't become more common as temperatures rise. NOAA/PHOTO LIBRARY/OAR/ERL/NSSL

hard way, with water supplies running low in boomtowns like Las Vegas (with reservoirs at only about 50 percent capacity in early 2008). Population growth means that the sort of once-a-decade dry spells that communities used to take in stride can become crises, says science writer John Fleck: "If you can't handle events within the normal range of variability, you're in trouble."

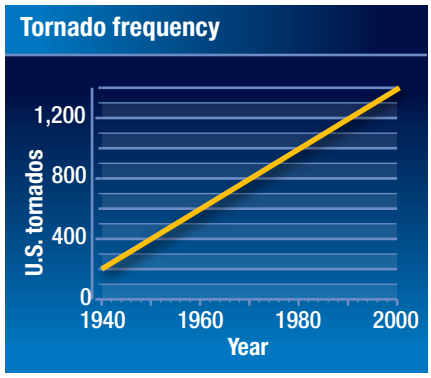
For all the nightmarish visions of rising seas swallowing Manhattan and Florida, it's the tap running dry (not the most cinematic of horror set-ups) that will challenge the survival of many towns and cities over the next few decades. Perhaps the ultimate symbol of this emerging crisis is the common bottle of store-bought water — often drawn from municipal taps, yet packaged, shipped, and chilled with the help of fossil fuels.

Stormy skies ahead?

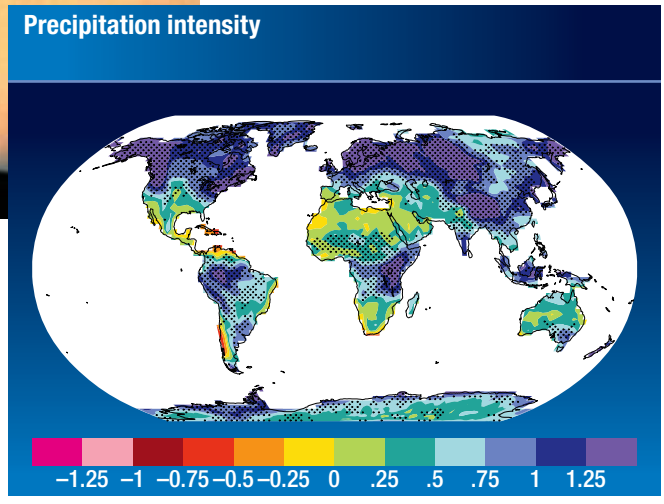
Just as the 2003 heat wave galvanized Europe, Hurricane Katrina shocked many Americans into taking climate change seriously. As with any weather event, there's no meteorological DNA test to confirm that Katrina was a child of global warming.

Plenty of strong hurricanes have missed New Orleans over the years. But there's circumstantial evidence that a warming climate helped nourish Katrina's strength. The hurricane drew its peak power as it passed over a deep vein of warm Gulf of Mexico waters, with surface sea temperatures topping 90° F (32° C) in spots — among the warmest ever measured there.

After a barrage of nine hurricanes struck the U.S. Gulf and Atlantic coasts in 2004 and 2005, only one made landfall in the next 2 years (Humberto, in 2007). That reprieve pulled attention away from the thorny question of whether climate change is making tropical cyclones — hurricanes, typhoons, and their ilk — stronger and more



MORE THAN 1,000 TORNADOS hit the United States each year, but most scientists think the climb reflects better observations. The number of the most violent tornados (EF4 and EF5) has stayed fairly constant at about 10 per year. *EXTREME WEATHER:* RICK JOHNSON, AFTER NOAA/SPC



A WETTER CLIMATE may not result from higher temperatures, but precipitation intensity will. This projection compares what to expect from 2080 to 2099 compared with 1980 to 1999. *EXTREME WEATHER:* RICK JOHNSON, AFTER IPCC

frequent. The Atlantic saw eight Category 5 storms from 2003 to 2007, while only four occurred in the preceding 20 years.

The number of named Atlantic systems also has increased markedly since the mid-1990s. Some scientists attribute this trend to multi-decadal cycling, and others, to global warming.

Worldwide, there's evidence that the proportion of tropical cyclones reaching Category 3 or higher has jumped in recent years. However, satellite-based monitoring began less than 50 years ago, making lengthier trends hard to diagnose.

As writer Chris Mooney points out in his book *Storm World*, the clash over hurricanes and global warming has its roots in more than 150 years of debate between weatherpeople steeped in observation and climate scientists who hark back to first principles of physics. "Long-standing personal and methodological schisms among meteorologists have, like a hurricane's steering currents, helped guide us to the present moment," writes Mooney.

The 2007 IPCC report claims that, on average, tropical cyclones will likely pack stronger winds and heavier rains as the century unfolds. But even as experts tussle over what climate change is doing to hurricanes, they agreed in a 2006 joint statement that coastal boomtowns needn't wait for the verdict: "The more urgent problem of our lemming-like march to the sea requires immediate and sustained attention."

As for tornados, they aren't a frequent threat outside of a few hotbeds — primarily North America, eastern India, and Bangladesh. Happily, there's no sign of an upsurge in truly violent twisters, the ones that cause the lion's share of deaths and damage.

It's true that North America and Europe now report far more tornados overall than in the 1950s, but that's most likely due to ever-increasing hordes of storm spotters and chasers. The count of U.S. twisters rated F3 or higher on the Fujita scale (or EF3 on the new Enhanced Fujita scale) hasn't changed much in half a century, averaging around 20 to 30 annually.

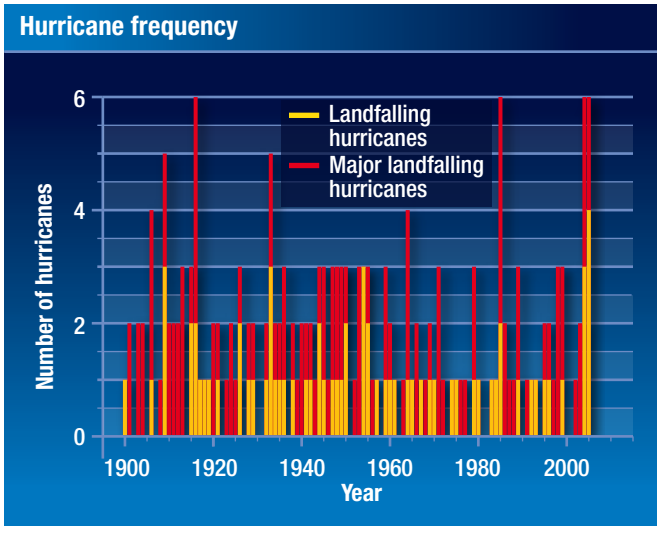
Recent work led by NASA's Tony DelGenio and Purdue University's Jeffrey Trapp has found that a warmer, wetter climate could boost the odds of severe thunderstorms across parts of the United States, despite weaker winds aloft. DelGenio and colleagues also found hints that tornados could become more prevalent.

However, the worst tornados emerge out of a delicate mix of atmospheric ingredients that isn't easily produced in nature or reproduced in a climate model. For now, most scientists aren't looking for a tornadic onslaught driven by climate change. "The increase in favorable environments for severe storms is much more likely to impact hail than tornados," says Harold Brooks at NOAA's National Severe Storms Laboratory.

How high the sea?

In the long run, surviving climate change may well mean pulling ourselves and our

HURRICANE ANDREW bears down on the Gulf Coast August 24, 1992, after it had devastated Florida. Andrew and other recent Category 5 storms suggest powerful hurricanes are on the increase. NASA/GSFC



MORE HURRICANES — or at least more intense hurricanes — should follow warmer ocean waters. The overall numbers seem inconclusive, although a spate of major hurricanes in this decade's first half leads some scientists to think the future is here. *EXTREME WEATHER:* RICK JOHNSON, AFTER NOAA

cities inland. Each year, the planet becomes more urbanized, and many of the fastest-growing cities are on coastlines. Counties bordering the sea hold more than half of the U.S. population.

Will a warming globe bring a painful end to our love affair with the seashore? We won't see the ocean swallow Miami next week, next year, or next decade. Yet without a massive global cutback in greenhouse-gas emissions, there's no avoiding a sea-level rise that would ultimately threaten the existence of many great cities.

How soon this will happen is a burning query without easy answers. Many filmgoers came away from the documentary *An Inconvenient Truth* shocked by its depictions of water swirling around Manhattan skyscrapers.

To get inundations like these, it'd take the loss of most or all of Greenland's vast ice sheet, a slab up to 2 miles (3.2 kilometers) high that covers more real estate than France, Spain, and Germany combined. If it melted completely, sea levels would rise by roughly 23 feet (7 meters). Melting of the West Antarctic Ice Sheet, less stable than the rest of that continent's ice, could boost sea levels by about 16 feet (5m).

If temperature-driven melting were the only process at work, then it could take 1,000 or more years for Greenland and West Antarctica to lose their ice. What raises the stakes is the process called dynamic thinning, where rivulets of meltwater trickle through the ice to its rocky base and lubricate the flow of glaciers seaward. Dynamic thinning is already a suspect in several dramatic speed-ups of glaciers along the Greenland coast. Climate models haven't yet come to grips with this process, and it's hard to observe directly, but many scientists fear it could speed the rate of sea-level rise well beyond current projections.

Even this faster track wouldn't put New York or London underwater in the next several decades. However, NASA's James Hansen, for one, speculates dynamic thinning and other wild cards could cause ice sheets to disintegrate in an accelerating mode as the century unfolds. "As a physicist, I find it almost inconceivable that business-as-usual climate change would not yield a sea-level change of the order of meters on the century timescale," Hansen wrote in a 2007 paper for *Environmental Research Letters*.

In its 2007 report, the IPCC separated dynamic thinning from its sea-level calculations. The report argues that it is a

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real concern, but the numbers are too iffy to include with other, better-understood components. These more-conservative projections call for a rise by 2080 to 2099 of anywhere from 7 to 23 inches (18 to 59cm), depending on how much we corral emissions and which model scientists use. That range may sound livable, but as with temperature, the devil is in the details.

Subsidence, tectonic plate motion, and other geologic factors mean some places will see higher water than others. Throw in the occasional wave-bearing storm, and you have the potential for a slow crisis punctuated by flash points.

"At most coasts in the world, even a meter-higher sea level wouldn't matter much. The problem comes suddenly during storms," says oceanographer Stefan Rahmstorf of the Potsdam Institute for Climate Impact Research.

A 2001 NASA study found a sea-level rise of one meter (3.28 feet) would put New York at risk of subway-flooding storm surges every 3 years. In today's climate, such events are expected only once a century.

The human hardship could be far worse in low-lying regions such as Bangladesh, where 15 million people live at elevations of less than one meter. The much-publicized tropical atolls of the Maldives and Tuvalu face serious risk, too, although natural processes that help replenish the reefs could allow the islanders a few years or decades before they're forced to bid farewell to their homelands.

What can we do?

In the past year, everyone from Greenpeace to George W. Bush has taken on climate change with various degrees of urgency. Egged on by 2007's Arctic melt and other ominous signs, politicians and citizens around the world are pushing for action, with the 2012 expiration date of the Kyoto Protocol looming in the background. And many corporations — mindful of the green handwriting on the wall — are reshaping how they operate, sensing a future with inevitable controls of some sort on carbon emissions.

Proposals for "geoengineering" our way out of global warming — for instance, by putting mirrors in space or Sun-blocking particles in the stratosphere — are getting more attention as back-pocket alternatives. But even the scientists examining such schemes acknowledge that the cleanest and safest approach is to add less carbon to the atmosphere in the first place.

In the meantime, we'll have to live with the changes that our past and present emissions guarantee. Some parts of Canada, northern Europe, and Russia may fare reasonably well, with warmer temperatures helping to stretch the growing season.

Other areas — especially developing countries in and near the subtropics — appear set to undergo wrenching bouts of drought, raising tensions over water supply. Wildfires likely will plague large stretches of western North America and Russia.

As these and other changes take shape, some countries will muddle through. Others will plan ahead. The Netherlands, for instance, is already contemplating "hydropoles" — floating cities.

Whatever unfolds, we're bound to be in for surprises, some pleasant and some not so nice. It's a safe bet we'll see the finite nature of our planet more clearly, and perhaps we'll relearn the Boy Scouts' durable motto: Be prepared. Along the way, we might even end up with a society — as well as a climate — that's far more resilient and sustainable.

Florida's sinking feeling

A RISE IN SEA LEVEL puts growing coastal populations at risk. In the United States, no region will feel the effects more than low-lying Florida. These snapshots show how much of the state will be underwater (red) with each 1 meter (40 inches) rise in sea level. J. WEISS AND J. OVERPECK (UNIVERSITY OF ARIZONA)

Nature's wicked spark

Scientists understood lightning's electrical nature more than 250 years ago, but thunderbolts remain a subject of intense research.

By Francis Reddy

On September 28, 2007, as a thunderstorm rolled over Oswego, New York, a siren designed to warn residents of problems at three nearby nuclear power plants began wailing — and wouldn't stop. A lightning strike had fried its electronics, which switched on the siren and simultaneously blocked controllers' attempts to shut the alarm down remotely. The wailing continued until a repair crew literally pulled the plug.

The incident highlights lightning's capricious side, but nature's biggest spark can exact a far more serious toll. According to the U.S. National Interagency Fire Center, lightning triggers some 12,000 wildfires every summer, mostly in the country's drier western half.

Each year, lightning kills some 50 people nationwide and inflicts life-long, debilitating injuries on perhaps 1,000 more. Experts estimate lightning's total social cost — from deaths, injuries, property damage, and interrupted economic activity — amounts to some $5 billion annually in the United States.

In the last 25 years, scientists discovered that aircraft and rockets can trigger lightning in clouds where it wouldn't otherwise occur. They found new forms of lightning that extend from the anvil tops of thunderclouds to the very edge of space. And satellites designed to detect energetic gamma rays from astrophysical sources like dying stars found

LIGHTNING STRUCK Geneva, Switzerland, as thunderstorms moved out of the northern Alps June 10, 2006. This view is from Mount Salève in France, just across the border. Each day, Earth receives more than 8 million cloud-to-ground lightning strikes. CHRISTOPHE SUAREZ

RIBBONS OF LIGHTNING illuminate the plume of Indonesia's Galunggung volcano during its third recorded eruption December 3, 1982. The volcano's roiling plume separates electrical charges just as thunderstorms do, with similar results. R. HADIAN/U.S. GEOLOGICAL SURVEY

THE BELL RINGER at the cathedral of St. Pol de Léon, Brittany, died when thunderstorms rocked the French coast April 14, 1718. Ringing the bell during a storm was thought to "break up" the lightning. FROM *THUNDER AND LIGHTNING*, 1869

that ordinary terrestrial thunderstorms create them, too.

Super spark

Lightning is a transient electrical discharge characterized by powerful currents surging along paths measured in miles. An average lightning bolt carries a current of some 20,000 amperes; the most powerful carry more than 300,000 amps. With about 2,000 thunderstorms occurring worldwide at any moment, lightning strikes the planet about 100 times each second, or more than 8.6 million times a day.

For more than 250 years, researchers have known that thunderstorms are electrical generators. Scientists agree with the overall picture: Colliding precipitation near a storm's freezing level — rain drops, ice crystals, and snow pellets — generates the charge. But that's where any consensus ends.

"The details of the microphysics involved still elude us," says Edward Mansell, who models storm electrification at the National Severe Storms Laboratory in Norman, Oklahoma. "So far, no one particular set of model parameters can reproduce the wide range of observed storm electrical behavior."

Somehow, a growing storm contains regions of negative and positive charge. Ultimately, it's this charge separation that makes lightning possible.

Usually, a thunderstorm carries a negative charge along its base and a positive charge at its top; pockets of either charge may form in the middle. Lightning bolts jump between regions carrying different electrical charges — for example, between different parts of the thunderstorm (intracloud lightning) or between the cloud and the ground. Lightning is nature's way of reuniting these separated charges. It's a spectacular attempt to restore electrical balance.

Although thunderstorms are lightning's predominant sources, snowstorms and the turbulent plumes of erupting volcanos can create similar electrical discharges. Even sandstorms can host lightning-like discharges measuring perhaps a few yards long.

An average lightning bolt delivers a current of some 20,000 amperes; the most powerful carry more than 300,000 amps.

Steps and strokes

As a thunderstorm matures, it develops a spreading, anvil-shaped top. Rain begins falling from its base. This negatively charged cloud base also repels negative charges on the ground directly below it. This creates a kind of positively charged "shadow."

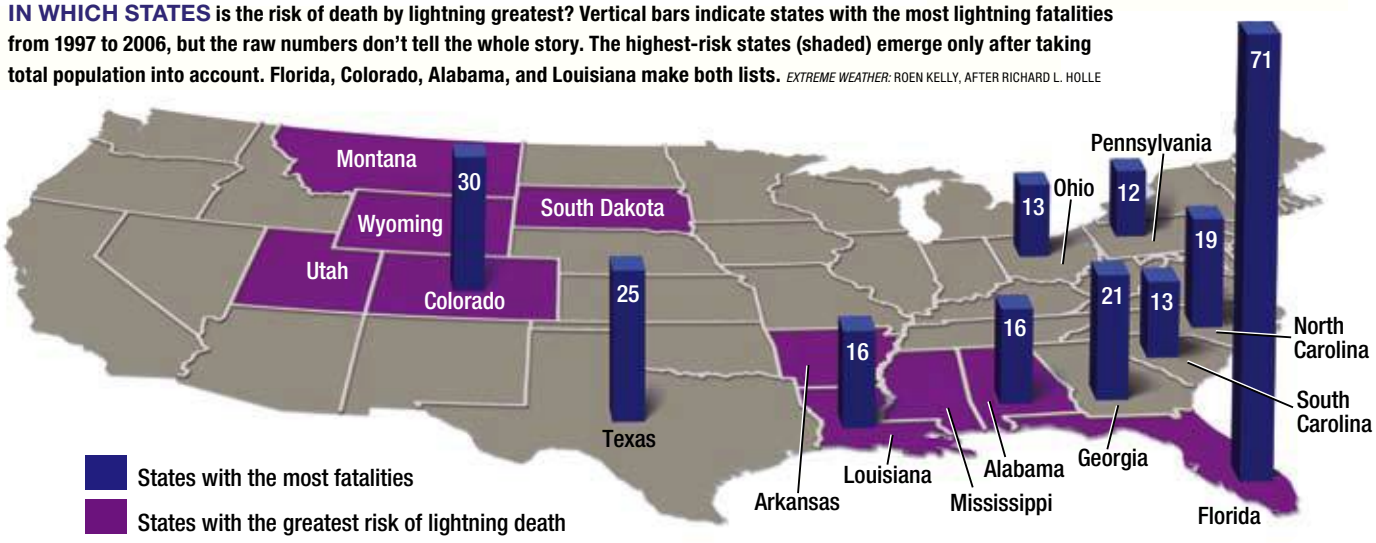
Somewhere in the storm, charge builds to the point where air, normally a good insulator, starts to leak electricity. Strong "feeler" currents called stepped leaders branch earthward at some 450,000 mph (720,000 km/h). Although special cameras can photograph stepped leaders, they're too fast and too faint to see with the naked eye.

After traveling a few miles, a stepped leader gets so close to an object on the ground — such as a church steeple, a tree, or a person — that the object starts shooting off its own feeler currents, called positive streamers. When a leader meets a streamer, they complete a circuit from cloud to ground.

What follows is a return stroke, a narrow channel that carries powerful electrical currents. This is the visible portion of a lightning flash.

U.S. lightning deaths by state, 1997–2006

IN WHICH STATES is the risk of death by lightning greatest? Vertical bars indicate states with the most lightning fatalities from 1997 to 2006, but the raw numbers don't tell the whole story. The highest-risk states (shaded) emerge only after taking total population into account. Florida, Colorado, Alabama, and Louisiana make both lists. *EXTREME WEATHER:* ROEN KELLY, AFTER RICHARD L. HOLLE



In a few microseconds, the stepped leader's 1,000-ampere current increases 30 or more times. A return stroke travels skyward at more than a third of the speed of light.

This rapid energy release heats the leader's branching channel to a temperature of 50,000° Fahrenheit (30,000° Celsius), or about 5 times hotter than the Sun's visible surface. White-hot air violently expands away from the channel, pushes on surrounding air, and creates a sound wave — the growl of thunder.

A lightning flash may end once the return stroke's current ceases to flow, but often something else happens. If a new pocket of charge becomes available at the channel's top, a fast-moving "dart leader" races toward the ground at nearly 7 million mph (11 million km/h) and initiates a new return stroke. This may happen several times. The lightning channel appears to flicker because the human eye can resolve the brightness changes between successive return strokes.

The foregoing describes a cloud-to-ground lightning flash that delivers negative electrical charge to the ground. This is the case in 90 percent of cloud-to-ground strikes around the globe. The remaining flashes deliver positive charge to ground. Because a storm's strongest positive-charge centers lie in its anvil top, positive strikes can carry more than 10 times the current of a negative strike originating at lower altitudes.

One unusual and especially dangerous type of cloud-to-ground discharge is a "bolt from the blue." Usually arising from a storm's trailing (updraft) side, the bolt travels horizontally away from the storm for several miles, then turns and strikes the ground. Researchers have documented these flashes as traveling more than 25 miles (40 km) from their parent storms.

Because the lightning channel extends so far from the storm, the bolt may appear to emerge from a clear sky. This is why the U.S. National Weather Service urges people to wait 30 minutes or more after the last audible thunder before they resume any outdoor activities.

Church bells to kites

The first attempts to protect structures from lightning involved the ill-advised practice of ringing church bells as thunderstorms approached. In the 18th century, church bells in Catholic countries bore inscriptions that included the Latin phrase *fulgara frango*: "I break up the lightning." A German book from this period records that, during a 33-year span, lightning struck 386 steeples and killed 103 bell ringers.

Church steeples are uniquely vulnerable because a descending stepped leader usually prefers to strike the tallest object around. The development of artillery in the 18th century, combined with the use of church vaults as weapons caches, meant inevitable disaster. The first recorded case occurred in 1769, when lightning struck the church tower at St. Nazaire in Brescia, Italy, and detonated

Safety first

In May 2000, Michael Utley of West Yarmouth, Massachusetts, never thought he'd be in danger on a golf course — until lightning struck. "What I learned ... is that lightning is an underrated killer that fries minds and turns bodies into charred shells," he wrote.

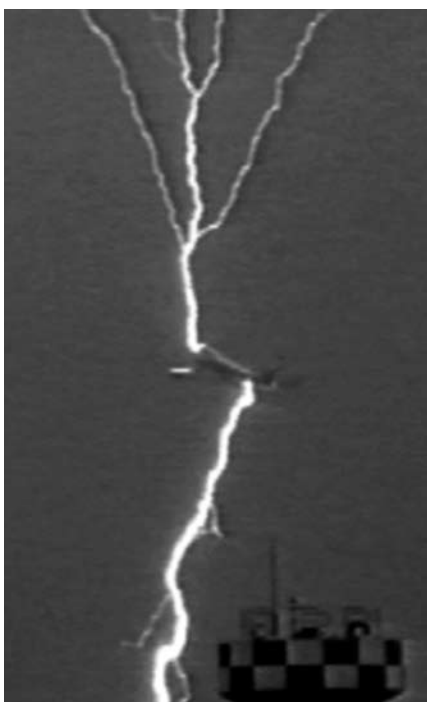
The bolt struck Utley's head and exited at his feet — it even blew off his golf shoes. The jolt damaged Utley's brain and stopped his heart. For 10 minutes, in rain and hail, his golfing partners performed cardio-pulmonary resuscitation (CPR) until paramedics arrived.

Thanks to them, Utley survived. It took him a month to recover his memory and considerably longer to cope with his remaining physical disabilities. After more than a year, he was still dealing with severe pain from damaged nerves and relearning basic motor skills.

"Most Americans consider thunderstorms minor, if dramatic, inconveniences," Utley wrote. He founded the web site Struckbylightning.org to spread the word about taking nature's mighty spark seriously.

Annually in the United States, lightning injuries outnumber deaths by more than 6 times. Because symptoms may not appear immediately, authorities suspect the real number is much higher. — *F. R.*

LIGHTNING SKITTERS over the canopy of a specially hardened F-106B fighter plane. From 1980 to 1986, the aircraft experienced 714 lightning strikes as part of NASA's Storm Hazards program. The aircraft's presence triggered about 90 percent of these bolts. NASA



AN AIRCRAFT encounters lightning as it takes off from Komatsu Air Base, Japan. The plane appears midway between upward- and downward-moving bolts. The aircraft's position indicates it triggered this flash. NOAA/NWS AND ZEN KAWASAKI (OSAKA UNIVERSITY)

100 tons of gunpowder stored beneath it. The resulting blast destroyed one-sixth of the city and killed 3,000 people.

Benjamin Franklin (1706–1790) initiated the first scientific study of lightning. In 1749, he noted the sparks he studied in his laboratory bore many similarities to lightning — including "giving light," "crooked directions," and "swift motions." Franklin wasn't the first to make these connections, but he went further, proposing experiments to prove they were the same phenomenon on vastly different scales. That same year, Franklin wrote that "houses, ships, and even towers and churches may be eventually secured from the strokes of lightning." This was his earliest recorded suggestion of the lightning rod.

In June or July of 1752, as a storm approached Philadelphia, Franklin famously flew a kite and drew a spark from a key to his knuckle, showing that lightning was, after all, electricity. But he wasn't the first to prove this point.

A French scientist named Thomas-François d'Alibard (1703–1799) had translated Franklin's book on electrical experiments. He decided to test the idea himself using a modified version of Franklin's "sentry box" experiment. In Marly, near Paris, at 2:20 P.M. on May 10, 1752, following a single thunderclap, a retired dragoon tending the experiment successfully drew sparks from an insulated iron rod. Others quickly replicated this dangerous experiment.

Triggering lightning

Fast-forward 220 years. In the 1970s, French scientists pioneered the use of small, solid-fuel rockets in an updated version of Franklin's kite experiment. The three-foot-tall (1 meter) rockets take off from tubes on a wooden launch platform. A spool of thin, tough wire runs from each rocket's tail to the launch pad, where ground instruments measure the local electrical field as a storm approaches.

When the air becomes sufficiently charged, scientists launch the rocket. Within seconds, lightning strikes the rocket and follows the wire into waiting instruments. The wire itself is vaporized.

Richard Richmond, a physicist at Wright-Patterson Air Force Base, Ohio, says that scientists were initially skeptical about the validity of results gained from these experiments. "The general feeling was that triggered lightning bolts were somehow different from the real thing. Now, we're using triggered lightning to see how well we can protect different objects," he explains.

The most famous example of rocket-triggered lightning occurred during the Apollo Moon missions. On November 14, 1969, as Apollo 12 prepared for launch at Florida's Kennedy Space Center, no one considered the possibility that the massive Saturn V rocket could induce lightning outside the presence of a thunderstorm. Although sensors indicated rapidly changing electrical fields 20 minutes before liftoff, no lightning was reported 6 hours before or after launch. Injecting the vehicle into an elevated electrical field triggered a flash where none otherwise would have occurred.

As Apollo 12 passed 6,300 feet (1,940 meters), 36.5 seconds into the flight, a cloud-to-ground flash struck the rocket and damaged nine nonessential sensors. The astronauts temporarily lost communication with controllers, warning lights flashed, alarms sounded, and spacecraft

A JAGGED CLOUD-TO-GROUND bolt splits the sky near Milwaukee in July 1987. Lightning that remains entirely within the clouds can reach lengths of 118 miles (190 km). Such bolts form at the leading edge of a squall line and extend horizontally back into the trailing clouds. FRANCIS REDDY

power fluctuated. Less than 16 seconds later, the rocket triggered an intracloud lightning bolt, but the mission was able to continue to a successful lunar landing and a safe return to Earth.

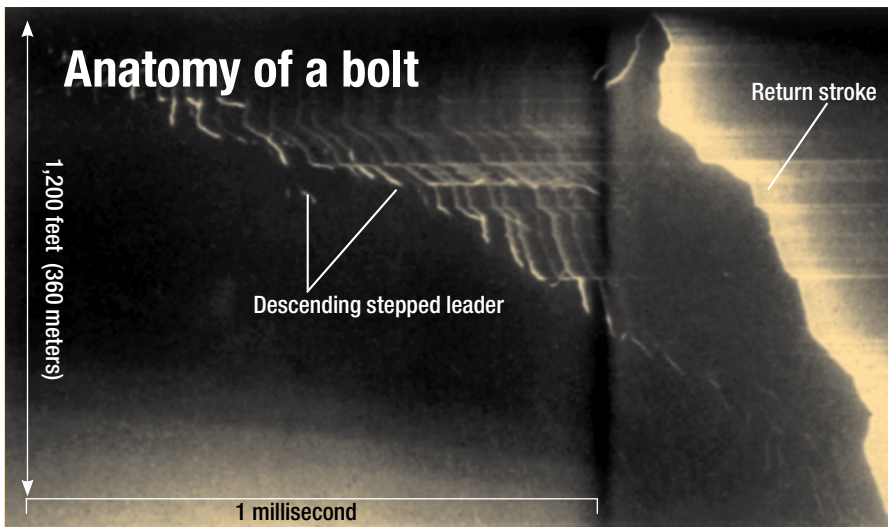
It could have been much worse — and on March 26, 1987, it was. That's when a rocket known as Atlas-Centaur 67 lifted off its pad at Cape Canaveral carrying a multimillion dollar satellite for the U.S. Navy. Weather conditions were similar to those accompanying Apollo 12's launch. At 49 seconds after launch, when the rocket reached 11,900 feet (3,636m), it triggered a cloud-to-ground lightning flash with at least four return strokes.

According to NASA's accident investigation board, the strike induced a transient current in the vehicle's onboard computer that changed a value at a single memory location. The computer issued a command to pitch the engine hard over. The rocket turned into the airstream at an excessive angle and began to break apart. At 70 seconds, the mission's Range Safety Officer destroyed the crippled vehicle and its payload.

While the aviation industry always has had a keen interest in lightning, it came as something of a surprise to learn that aircraft themselves initiate 90 percent of strikes. One of the studies that forced this conclusion home was NASA's Storm Hazards program. From 1980 to 1986, researchers flew a specially hardened, heavily instrumented F-106B fighter jet into thunderstorms with the purpose of taking lightning strikes.

Whenever summer afternoons brewed thunderclouds near Wallops Flight Center in Virginia, one of the group's project engineers teamed up with a pilot and climbed aboard the obsolete fighter. It flew 1,500 passes through thunderstorms and received 714 lightning strikes.

For 216 of those strikes, Storm Hazards' lead researcher Bruce Fisher sat in the rear seat tending to dozens of instruments. "Once you get inside the thunderstorm," he says, "the visibility really drops. It's like being inside a well-lighted pillow. You can't see very far — sometimes you can't even see the wing tips of the plane. And you're also getting bounced around a lot by turbulence."



SWISS HIGH VOLTAGE RESEARCH COMMITTEE

IN THE EARLY 1960S, researchers developed a specialized moving-film camera to catch stepped leaders in the act. The leader seen here is descending the final 1,200 feet (360 meters) to a strike on Mount San Salvatore near Lugano, Switzerland. Scientists greatly enhanced the leader's brightness. In less than 2 milliseconds, the stepped leader races to ground and triggers a return stroke.

Fisher says his engineers typically saw about 60 percent of the bolts that hit them. "The most spectacular one I've seen struck the plane's nose boom and came down the middle of the canopy — over the pilot's head and right over me. It was shaped like a corkscrew, and as it came past me it broke apart," he recalls. "Chunks of the lightning channel drifted past the canopy on both sides. It seemed to move in slow motion, but actually came down the airplane rather rapidly."

Most of the bolts that struck NASA's F-106B first latched onto its nose and then swept along the fuselage. The plane's aluminum body shielded everything inside it from lightning's whopping jolt. Electricity flowed along the craft's metallic skin and couldn't enter the plane. The same principle keeps occupants safe when lightning strikes an automobile.

According to Anderson Plummer, chief engineer of Lightning Technologies, Inc., in Pittsfield, Massachusetts, every commercial aircraft in service has been struck by lightning. In Europe and some other parts of the world, commercial aircraft may receive as many as three strikes

LIGHTNING'S ZAP converts inert atmospheric nitrogen (N_2) into nitrogen oxides plants can use. Lightning produces 16 million tons of these nutrients each year. FRANCIS REDDY

a year. "We think the shorter flight times there equate to more time spent at altitudes conducive to lightning, between 5,000 and 20,000 feet [1,500 to 6,100m]," he explains.

Plummer's company develops and tests lightning-protection gear for aviation. "The lightning damage of greatest concern is on the fuselage," he says.

As a lightning channel sweeps aft, it attaches to many points on an aircraft's body. "There may be 20 or 30 attachment points for each encounter, and each one requires a repair," Plummer explains. While such damage is superficial, usually minor pitting of the airframe's metal, it can lead to corrosion and must be fixed.

Sprites, jets, and elves

Just as aviation experts were getting used to the idea that most aircraft strikes are self-inflicted, lightning experts were in for a surprise of their own. They were stunned in 1989 when researchers discovered the first of several new types of discharge in the clear air above nighttime thunderstorms.

In fact, a few historical eyewitness accounts had hinted at them. The earliest report comes from 1886, when a ship's captain, T. MacKenzie, reported strange flashes of colored light in the upper reaches of a storm seen from Kingston, Jamaica: "Continuous darts of light … ascended to a considerable altitude, resembling rockets more than lightning."

Other reports described "flames appearing to rise from the top of the cloud" or a discharge that "assumed a shape similar to roots of a tree in an inverted position." In the 1920s, Scottish physicist Charles Thomson Rees Wilson predicted the existence of brief flashes of light high above large thunderstorms. Years later, the Nobel laureate even saw one himself.

On July 6, 1989, John Winckler and associates at the University of Minnesota were testing a low-light-level video camera by recording images of stars and a distant lightning storm. Unexpectedly, the camera caught twin flashes of light rising high above the storm. These events would come to be called sprites.

In 1993, two independent groups — one led by Davis Sentman of the University of Alaska, Fairbanks, the other led by Walter Lyons of FMA Research — set up field programs to target new luminous phenomena in thunderstorms. Before long, researchers collected a menagerie of fancifully named events, such as sprites, blue jets, and blue starters — the rocket-like lightning Captain MacKenzie described.

Scientists predicted one type of thunderstorm glow in 1991, a year before they were first observed. Called elves, they last less than a millisecond. Researchers first identified these faint, horizontal flashes on video images from the space shuttle in 1992. Elves form when a powerful cloud-to-ground strike generates a pulse of electromagnetic radiation. This heats and ionizes air about 60 miles (97 km) high, resulting in a brief expanding glow.

Sprites and jets, on the other hand, are electrical discharges — lightning's peculiar cousins. Christopher Barrington-Leigh, now at the University of British Columbia, studied elves and sprites for his doctoral work at Stanford University. "Sprites are brief even on intensified video cameras, so watching these things I learned to blink only one eye at a time," he recalls. "There's no motion visible at all unless you have a millisecond–level camera." Jets, on the other hand, "move quickly, but slow enough to perceive motion." Sprites almost always are associated with powerful positive cloud-to-ground lightning, whereas blue jets show no direct association with cloud-to-ground strikes.

A SPRITE climbed more than 53 miles (85 km) high in this July 4, 1994, image — the first color picture of the phenomenon. GEOPHYSICAL INSTITUTE, UNIVERSITY OF ALASKA, FAIRBANKS

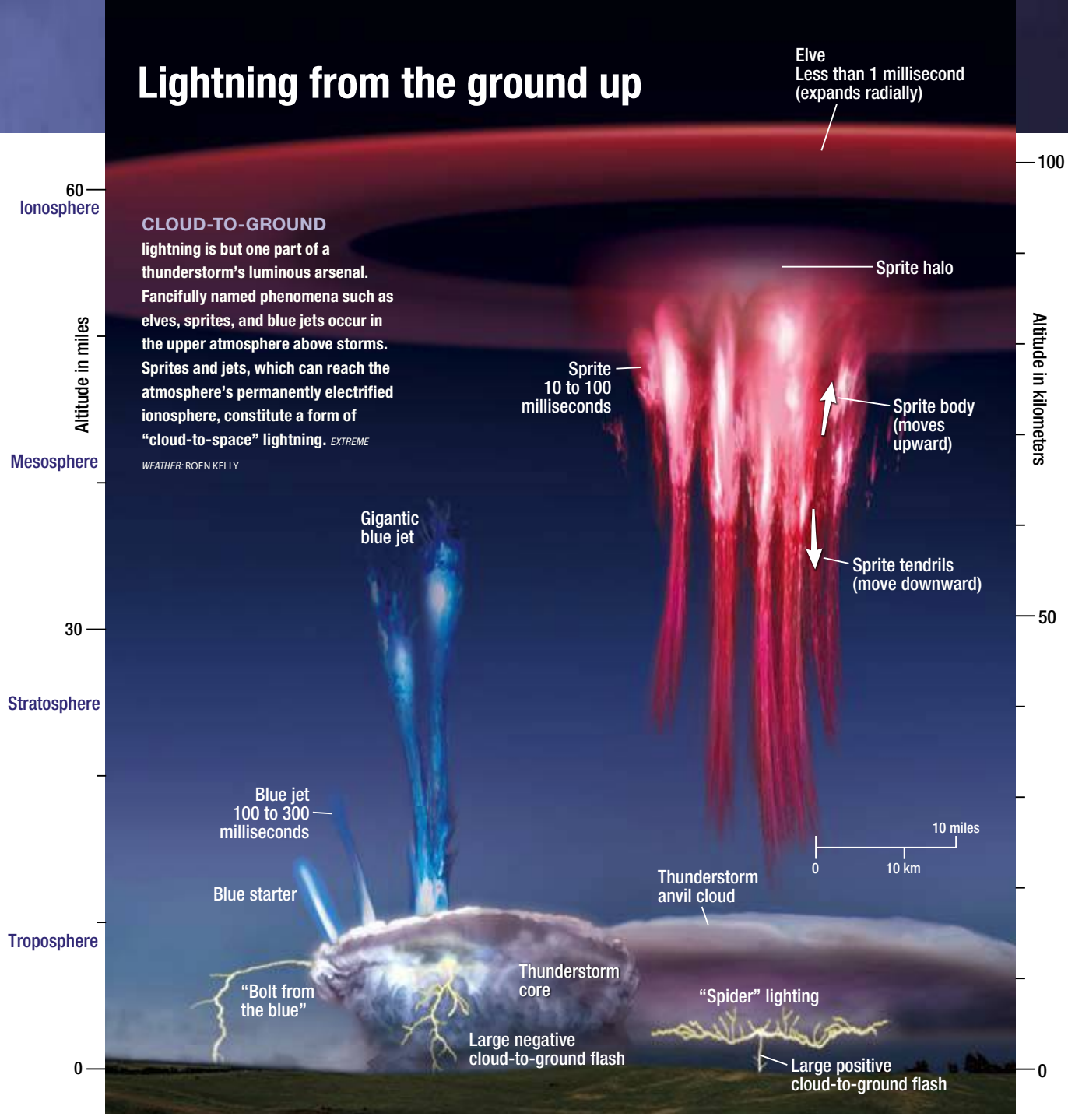
Thunderstorms held more surprises. In 1994, using NASA's Compton Gamma-ray Observatory, Gerald Fishman at NASA's Marshall Space Flight Center and his colleagues detected millisecond gamma-ray pulses from Earth's atmosphere. These events, called terrestrial gamma-ray flashes (TGFs), produce the most energetic radiation on Earth.

These events, called terrestrial gamma-ray flashes, produce the most energetic radiation on Earth.

Researchers came to favor an explanation where powerful lightning bolts, followed by the chance impact of a high-velocity particle, triggered a runaway breakdown high above a storm. An energetic electron, liberated either by an atom's decay or the intrusion of a cosmic ray, ionizes many air molecules. The thundercloud's intense electric fields then accelerate the particles, and the fast-moving electrons emit gamma rays as surrounding air slows them down.

In 2005, studies led by Steve Cummer at Duke University in North Carolina linked TGFs in time and place to lightning from Caribbean thunderstorms. TGFs actually precede the lightning strikes, which in any case are too weak to trigger high-altitude runaway breakdown.

Francis Reddy *is a senior editor of* Astronomy.



Cummer concludes that strong fields in or just above the thundercloud must instead be triggering TGFs. "The only real possibility is that it's much closer to the cloud top, and linked to something else happening inside the cloud," he says.

On January 6, 2007, as winter thunderstorms rumbled over the Sea of Japan, ground-based gamma-ray detectors operated by Japan's University of Tokyo and RIKEN Cosmic Radiation Laboratory provided detailed information on the energy and timing of TGFs. According to a study led by Teruaki Enoto at the University of Tokyo, the array detected TGFs lasting 40 seconds — far longer than those seen from satellites.

"The logical solution to the puzzle is that, rather than being caused by lightning, these things may be the cause of lightning breakdown," explains Barrington-Leigh. Scientists still don't understand how a thunderstorm's electrical charges break down air's natural insulation — that is, make it leak electricity — to initiate a lightning strike in the first place.

"People hadn't thought about the possibility of this sort of breakdown because it requires electric fields to be sustained for very long distances," he says. "It looks now like it might be quite common. It might actually be behind all lightning."

Whatever its origin, lightning in all its guises remains one of nature's grandest spectacles. The effort to understand how it works takes researchers from the roiling interiors of thunderclouds to the very edge of space and, possibly, beyond. Electron beams and gamma rays from thunderstorms may have as-yet-unappreciated influences on the belts of electrically charged particles surrounding Earth.

That's quite a journey from Ben Franklin's kite.

Where is Earth wettest and driest?

Colliding warm and cold fronts can produce unbelievable amounts of rain or snow. Here are Earth's record spots.

By Laura Baird

From light drizzle to freezing rain, precipitation takes different forms. Too much rain can cause floods, while snow, hail, and sleet bring their own troubles. The type of precipitation that falls corresponds to changes in local temperature and air pressure. As warm air expands and rises, it can't hold onto its moisture, so it forms clouds and releases rain. Sleet forms when the water droplets freeze during their freefall back to Earth's surface.

Latitude, altitude, and topography can conspire to produce some soggy or snowy places. For example, thunderstorms drench Kampala, Uganda, 242 days a year on average, while some places in Chile's Atacama Desert haven't seen a raindrop in centuries.

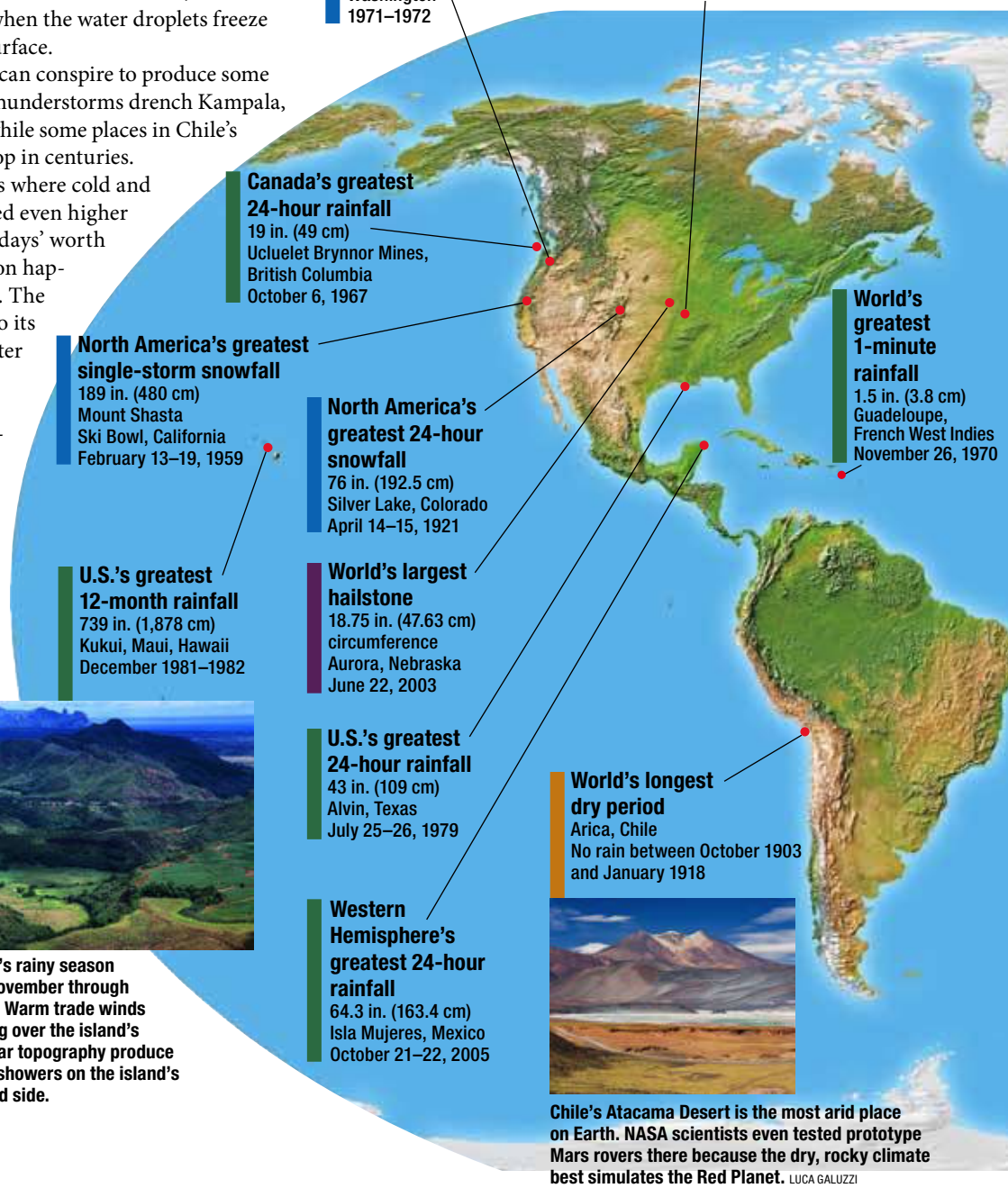
Extreme precipitation often occurs where cold and warm air masses meet. Warm air lifted even higher by an incoming cold front can create days' worth of rain or snow. A similar phenomenon happens when air moves over mountains. The updraft can cool moisture-laden air to its dew point, the temperature where water vapor condenses.

Such uplift, coupled with tropical cyclone Hyacinthe, resulted in the largest 12-hour and 5-day rainfalls on record. On Réunion Island in the Indian Ocean, narrow valleys funnel wind up mountains some 10,000 feet (3,000 meters) high. In January 1980, a 5-day rainfall totaled 169.3 inches (430 centimeters), which approaches the theoretical maximum.

Another volcanic island is the United States' wettest spot: Hawaii's Maui. Between December 1981 and 1982, the city of Kukui recorded 739 inches (1,878 cm) of rain. The island lies in the path of the warm trade winds, which cool dramatically when they blow over Maui's mountaintops. Nonetheless, the same rain nourishes the lush, green landscape that makes the Hawaiian Islands among the world's top tourist destinations.

Hawaii's rainy season runs November through March. Warm trade winds blowing over the island's irregular topography produce heavy showers on the island's leeward side.

Mount Rainier in Washington is an active volcano that tops out at 14,410 feet (4,390m) above sea level. Annually, thousands of people attempt to reach the summit — only about half succeed. USGS

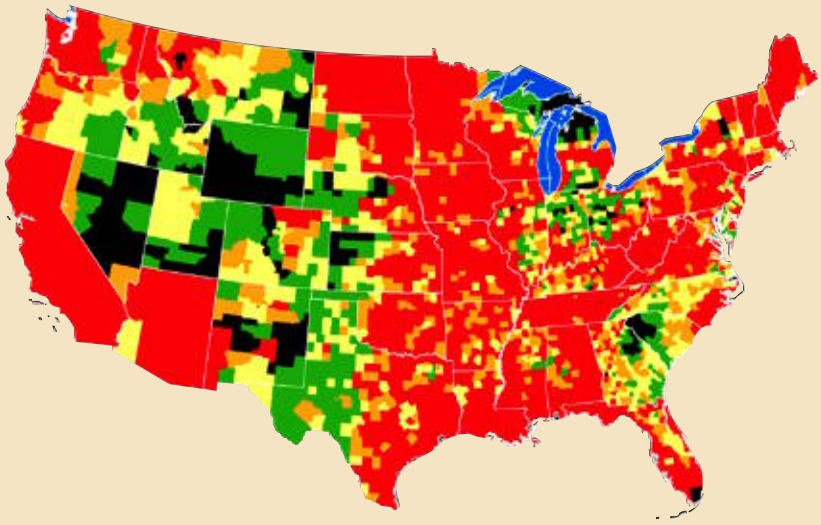


Chile's Atacama Desert is the most arid place on Earth. NASA scientists even tested prototype Mars rovers there because the dry, rocky climate best simulates the Red Planet. LUCA GALUZZI

Floods in the United States

This map shows the number of times between June 1, 1965, and June 1, 2003, that the U.S. President has declared a county a national disaster zone because of floods. Green signifies one declaration; yellow, two; orange, three; and red, four or more. Rising water results from major rain storms and melting snow, but also from inadequate drainage and the failure of infrastructure like levees and dams.

The growing concentration of coastal developments during the past 50 years has placed many more people and economic assets in areas susceptible to rising water. In 2003, 153 million people (53 percent of America's population) lived in coastal counties, which account for only 17 percent of the nation's land area. — *L. B.*



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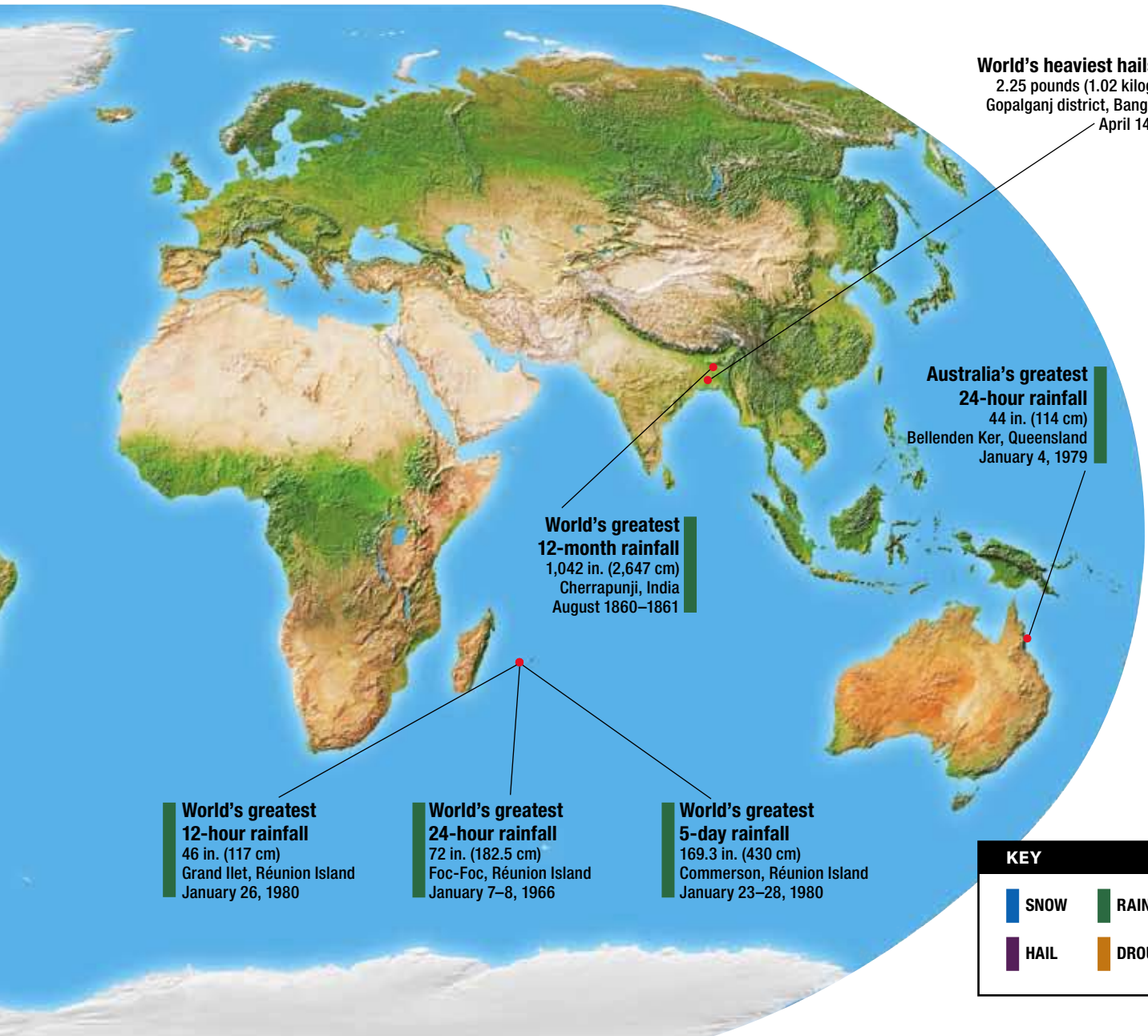


NASA EARTH OBSERVATORY/FRANCIS REDDY/*EXTREME WEATHER:* JAY SMITH

STRATFORD, TEXAS, braces for an approaching dust storm April 18, 1935. This dust-filled cloud looms over the Texas landscape and promises to envelop all in its path. NOAA GEORGE E. MARSH ALBUM

When the sky rains earth

Wind's driving force can produce enormous, Sun-blocking dust clouds that devastate everything in their paths.

By Keith C. Heidorn

The Dust Bowl years define an extreme weather period in U.S. history: a decade of withering drought during the 1930s that spanned the Plains states. Then, wind and dust fueled devastating storms that turned day to night and transformed landscapes. But such destructive dust clouds are not just relics of the past.

Dust storms still roam the nation each year. In arid parts of the world, such as the Middle East and western China, strong winds whip dust and sand into the air and form storms. The conditions may last days or weeks and cover thousands of square miles. Around the world, dust storms have earned special names: "black blizzard" and "black roller" in the United States and Canada; the "haboob," the "ghibli," and the "simoom" in the Sahara region of North Africa and the Middle East; the "zonda" in Argentina; and the "brickfielder" in Australia.

Dust originates from drought-withered lake beds and deserts, areas where vegetative cover has died out due to drought. Drought in agricultural regions, where cropland becomes barren and dry, provides ideal conditions for dust storms, as the Dust Bowl years attest.

Meteorologists use the term "dust storm" for weather events with particular characteristics. A dust storm requires blowing dust that reduces visibility to 5/8 mile (1 kilometer) or less. When blowing dust reduces visibility to less than 5/16 mile (500 meters), the situation becomes a severe dust storm. Major dust storms can persist for several days.

From dust to dust storm

Such calamities start with a process known as aeolian transport, the process whereby wind picks up and transports surface particles. If the wind gusts for a short time, a simple blowing-dust event may occur. However, when the wind blows strong and steady and raises lots of dust, a dust storm can result.

Although a variety of weather conditions can generate a dust storm, storms usually fall within one of two main categories: "convective events" and "large-scale, non-convective events." Convective-event dust storms are associated with thunderstorm outflows or downbursts. The duration of these dust storms depends on the processes that form them. A microburst may create a dust storm lasting a few seconds, while downburst or outflow dust storms may last several minutes. Wind associated with a dry squall line may produce dust storms lasting hours.

Convective-event dust storms in the United States usually occur during afternoons in late spring or summer, when daytime heating peaks. Large-scale, non-convective events arise from sustained high-surface winds that are often associated with cyclonic (low-pressure) wind storms.

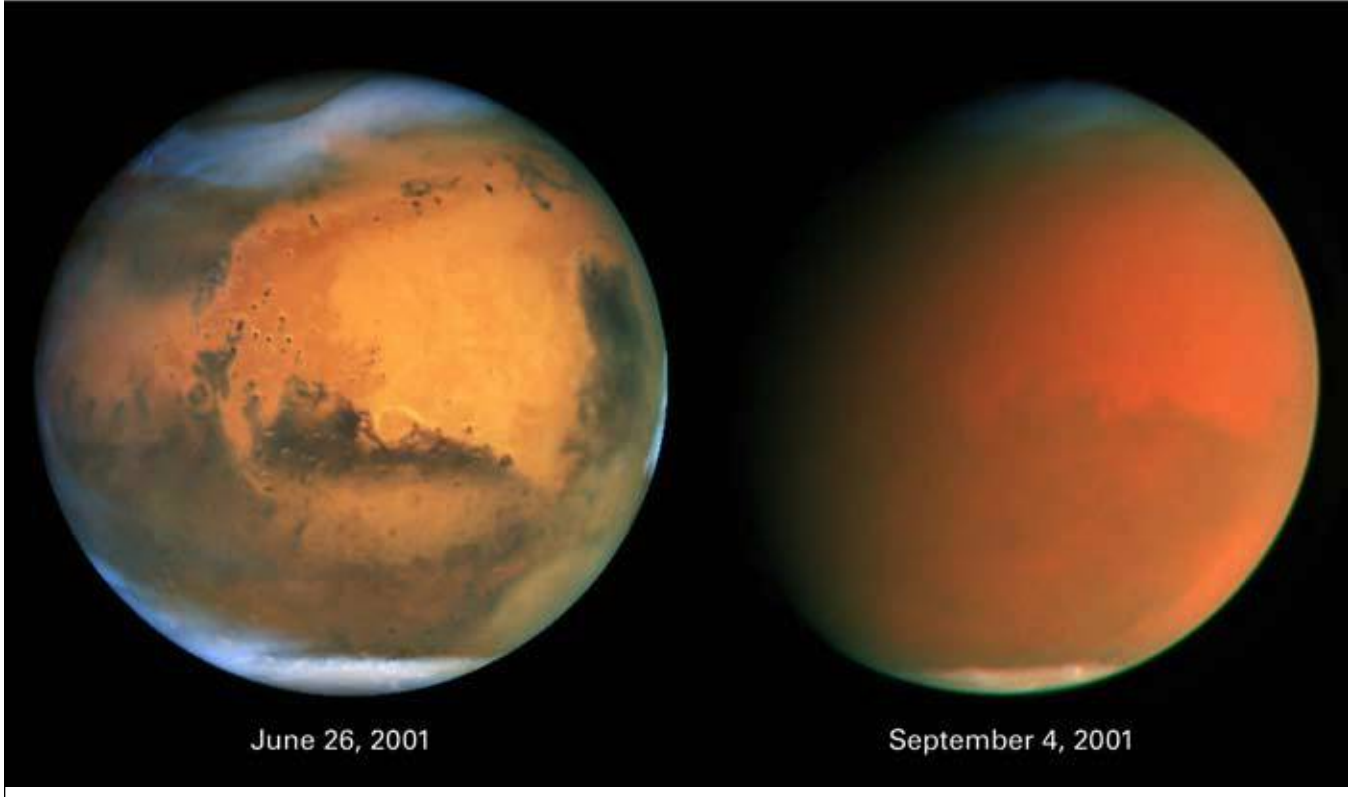
Such dust storms can last hours or days depending on the conditions. In the United States, these storms generally occur during late winter or early spring, when extreme pressure gradients produce high winds over dry, bare surfaces. Strong winds associated with low-pressure cells and passing fronts produce about two-thirds of all U.S. dust storms.

Local dust storms

Strong winds can lift dust to altitudes as high as 15,000 feet (4,600 meters). When particles reach such high altitudes, upper-level winds carry them for a long distance before the dust settles back to Earth. Storms end when dust-free air mixes with dusty air or when the wind speed drops.

DRIFTING DUST engulfs abandoned farm equipment in Kansas. This image, taken October 4, 1935, shows the impact large dust storms have on people and agriculture.

NOAA PHOTO LIBRARY



A GLOBAL dust storm obscures surface features on Mars. The Hubble Space Telescope's Wide Field and Planetary Camera 2 captured these images in 2001. The image taken June 26 (left) shows the Red Planet before the dust storm, while the photo shot September 4 (right) reveals little of Mars' surface. NASA/ J. BELL (CORNELL)/ M. WOLFF (SSI)/HUBBLE HERITAGE TEAM (STScI/AURA)

MARS' NORTH POLE experiences dust storms each martian spring as its ice cap thaws. The Mars Global Surveyor Mars Orbiter Camera snapped this image of at least three dust storms December 24, 2002. NASA/JPL/MSSS

A dust storm blankets Mars

Huge planetary dust storms sometimes cover our sister planet Mars, obscuring the Red Planet's surface features from view. One such storm struck in July 2007 and jeopardized NASA's Mars Rover mission.

The giant dust storm covered nearly all 7 million square miles (18 million square km) of Mars' southern hemisphere. A desert planet, Mars spawns such global dust storms about once every 3 years. Our watery planet Earth, where vegetation or ice covers much of the land surfaces, never has dust storms of the same magnitude as Mars. — K. H.

Most dust storms run their course over a local or regional scale — extending from miles to a hundred miles. However, larger storms, such as the great dust storms of the Dust Bowl years, may extend up to 1,000 miles (1,600 km).

Global dust storms

In the last few decades, scientists have observed surface dust transported thousands of miles from its source.

For more than a century, scientists have known that dust lofted high into the atmosphere by volcanos travels around the globe and remains suspended there for many years. The famous 1883 eruption on Krakatoa, a volcanic island in Indonesia, shot dust into the stratosphere, reducing sunlight and coloring the sky for several years.

Modern satellites let scientists observe dust clouds traversing the oceans and depositing dust onto faraway surfaces. One of the largest global dust storms arose in April 2001. That spring, an Asian storm kicked up a million-ton dust cloud from the Gobi and Takla Makan deserts in Mongolia and China, respectively.

Global wind streams pushed the 1,250-mile-long (2,000 km) dust cloud off the Asian mainland and across the North Pacific Ocean. The dust, visible from weather satellites, reached North America's West Coast April 12. It crossed the continent in 2 days and then moved out into the Atlantic Ocean. When satellites last detected this dust cloud April 24, it had traversed two-thirds of the Atlantic on its way toward England. As it passed over Great Britain, the dust reduced visibility for an entire day and painted the sky a hazy yellow.

Weather satellites also show the Sahara Desert sends huge dust clouds across northern Africa, into Europe, and over the Atlantic Ocean. Some storms reach the Caribbean waters and even the Amazon rain forests. Some African dust storms have prompted the U.S. National Weather Service Office in San Juan, Puerto Rico, to issue air-pollution alerts.

Dust storms past and present

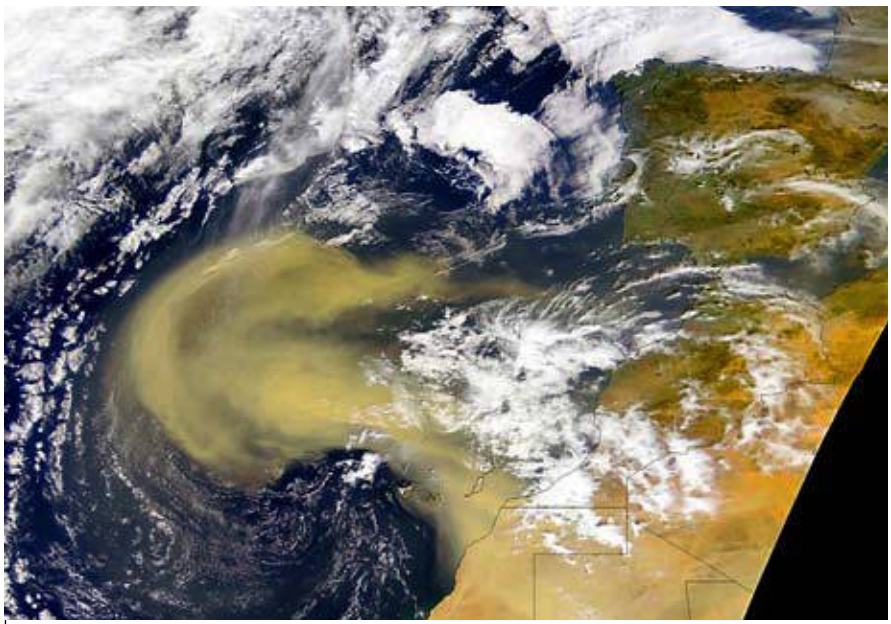
The worst "black blizzard" to hit the United States during the Dust Bowl era began Sunday, April 14, 1935, a day that would become known as Black Sunday. The storm arose in eastern Colorado and trekked through western Kansas to Texas and Oklahoma. The airborne dust turned day into night, leading many to believe the world was coming to an end.

Just past midday, the massive storm darkened the Kansas sky over Dodge City. On the horizon, a bank of dirty black clouds grew larger and more ominous.

The roiling clouds blotted out the Sun, then obscured surface lights blazing because of the daytime darkness. A dust cloud some 8,000 feet (2,400 meters) high roared in on 60 mph (96 km/h), gale-force winds and enveloped all, knocking visibility to zero and silt-blasting everything in sight. Winds drove dust clouds so thick that total darkness prevailed for 40 minutes, followed by 3 hours of semi-darkness.

The storm eventually covered much of the nation east of the Mississippi River. The storm deposited an estimated 12 million pounds (5.4 million kilograms) of dust on Chicago — 4 pounds (1.8 kg) for each city resident.

The dust storm later rolled over the Atlantic Seaboard, darkening the skies over New York and Washington. Ships as far as 300 miles (500 km) out to sea reported dust falling on their decks.



DUST STORMS on Mars (top) look similar to those on Earth (bottom). The process of aeolian transport, which relies on wind, lifts dust particles into massive dust clouds on both planets.

TOP: NASA/JPL/MSSS; BOTTOM: NASA/GSFC AND ORBIMAGE/SEAWIFS PROJECT

The thick dust damaged crops, livestock, buildings, and electrical service as it penetrated structures and covered everything in its path. People caught out in the storm covered their faces with handkerchiefs or small rags to avoid inhaling the dust.

Being indoors did not always afford protection, as the minute dust particles penetrated buildings through doorways and windows not firmly sealed. Many people caught repeatedly in dust storms developed respiratory diseases known colloquially as "dust pneumonia."

We like to think such black blizzards are things of the past, and while an event of Black Sunday's proportions has not yet been repeated, extensive dust storms still roll across the western United States. One

Keith C. Heidorn *has nearly 40 years of experience in meteorology, climatology, air-quality assessment, and education. His most recent book,* And Now … the Weather *(Fifth House Books), was released in July 2005.*

MARINES WATCH as a massive wall of sand encroaches upon their base in Al Asad, Iraq, April 26, 2005. The wind-borne particles turned the sky orange. The dust storm, which formed near the border between Syria and Jordan, reached a height of 4,000 to 5,000 feet (1,200 to 1,500 meters). U.S.M.C.

DUST-STORM WARNINGS

When the U.S. National Weather Service issues dust-storm advisories and warnings, they may apply to local conditions or to a large area. In situations where blowing dust reduces visibility down to ¼ mile (400 meters), and the reduction in visibility poses an inconvenience, the Weather Service will issue a blowing-dust advisory. When winds generate blowing dust that reduces visibilities to ¼ mile (400m) or less and poses a threat to safety and property, the Weather Service issues a dust-storm warning. — *K. H.*

such gale struck Texas February 24, 2007. Originating near Amarillo, in west Texas, the storm moved across north Texas and passed over the Dallas-Fort Worth metropolitan area. The strong winds and blowing dust caused considerable property damage and delayed air traffic at the Dallas-Fort Worth Airport. Many Texans under the fury's path suffered allergic reactions and respiratory ailments requiring medical attention.

Dust storms forming over desert regions of China and Mongolia have plagued eastern Asia during the last 2 decades, claiming a significant human toll. During such an event in May 1993, 85 people died in northwestern China.

Dust storms and life

After decades of trans-Atlantic dust measurements, Joe Prospero of the University of Miami's Rosenstiel School of Marine and Atmospheric Sciences estimates some 14.3 million tons (13 million metric tons) of African dust fall on South America's North Amazon Basin every year. A single Sahara dust storm may transport more than 310,000 tons (280,000 metric tons).

Several research teams analyzed the Sahara dust's composition. The teams found Saharan dust often provides plants with otherwise lacking nutrients — in particular, iron and phosphorus.

In the Amazon basin, Saharan dust provides the main mineral injection that fertilizes the forests. In Florida's coastal waters, however, the dust may cause toxic algal blooms known as red tides.

While African dusts increase biological productivity by infusing missing micronutrients, they also carry minute life-forms. Microbiologists have cultured more than 100 species of bacteria, viruses, and fungi from airborne dust. Approximately one-third are pathogens that cause disease in plants, animals, or people. These pathogens include pseudomonads, which give rise to ear and skin infections in humans, and the microbes responsible

A WALL OF DUST threatens Marines and their equipment in Al Asad, the second-largest air base in Iraq, April 26, 2005. U.S.M.C.

for sugar-cane rust, potato dry rot, and banana leaf spot.

An alarming decline in Caribbean coral reefs since the late 1970s has led scientists to suspect the decline may be due, in part, to pathogens imported on African dust. Major reef die-offs correspond to peak years of African dust deposition in the Caribbean. Dale Griffin of the U.S. Geological Survey in St. Petersburg, Florida, and his team found one fungus, Aspergillus sydowii, causes disease in the delicate Caribbean corals known as sea fans.

The great dust storms that sweep off the Asian continent also impact the aquatic and terrestrial biospheres. These storms bring essential nutrients to rain forests in Hawaii and other remote islands in the Pacific Ocean. Marine biologists also believe Asian dust crossing the Pacific causes mid-ocean algal blooms by fertilizing them with iron, a mineral deficient in open ocean waters under normal circumstances.

Such was the case in spring 2001, when two robotic Carbon Explorer floats located in the North Pacific recorded the rapid growth of phytoplankton. The robots recorded a near doubling of biomass over a 2-week period following the passage of an Asian dust cloud.

DUST PARTICLES CREEP, leap, or are held aloft by wind through a process known as "aeolian transport." During a dust storm, wind removes loose material from Earth's surface. The dust particles may "creep" forward, hop along in a series of leaps called "saltation," or remain airborne, called "suspension." A dust storm often produces all three methods of aeolian transport.

EXTREME WEATHER: ROEN KELLY, AFTER KEITH C. HEIDORN

Understanding aeolian transport

Aeolian transport (after Aeolus, the Greek god of the wind) describes particles moved by the wind. Dust becomes airborne when moderate to strong winds traverse land with little vegetation, pick up particles of sand, dust, soil, and other debris, and send them skyward.

Aeolian transport may occur through suspension, saltation, or creep of the particles. Often, a dust storm exhibits all three methods.

Wind holds the smallest dust particles in the atmosphere through suspension. Suspension occurs when upward air currents are strong enough to support particles thrown into the air and can hold them aloft indefinitely.

Typical wind speeds near the ground will suspend particles with diameters less than 8/1,000 inch (0.2 millimeter). Strong winds may lift suspended dust particles thousands of feet, and transport them thousands of miles downwind.

Saltation (Latin for "leaping") moves small particles forward through a series of jumps or skips, like a game of leap-frog. Under typical wind speeds, saltation normally lifts particles no larger than 0.4 inch (1 centimeter) in diameter above the ground about 3 to 7 feet (1 to 2m). Once lifted into the air, these fine soil particles can drift across Earth's surface about 4 times farther downwind than the height they attain above the ground.

But these dust particles are too heavy to remain airborne for long and remain suspended for only a brief moment. However, a saltating particle may then hit another particle as it returns to Earth. The struck particle will jump up and forward to continue the saltation process. At high wind speeds, saltation occurs more or less continuously.

From a distance, a field of saltating particles appears as if constantly suspended, creating a fuzzy layer next to the ground. When saltating particles hit larger particles too heavy to hop, they nudge the larger grains (up to 6 times larger than saltating particles) slightly and slowly forward, a sliding and rolling movement known as "creep." Creep usually requires a wind speed exceeding 10 mph (16 km/h). — *K. H.*

NASA's SeaWiFS satellite concurrently detected the sea surface turning greener with chlorophyll, confirming the phytoplankton's growth.

Dust storms and climate change

Oceanic phytoplankton remove large quantities of carbon dioxide from the atmosphere. Because of this, we need to better understand phytoplankton's role in climate change. According to Carbon Explorer's project leader, oceanographer James Bishop of the Lawrence-Berkeley National Laboratory, understanding this process may determine whether or not large-scale iron fertilization of the ocean would slow global warming.

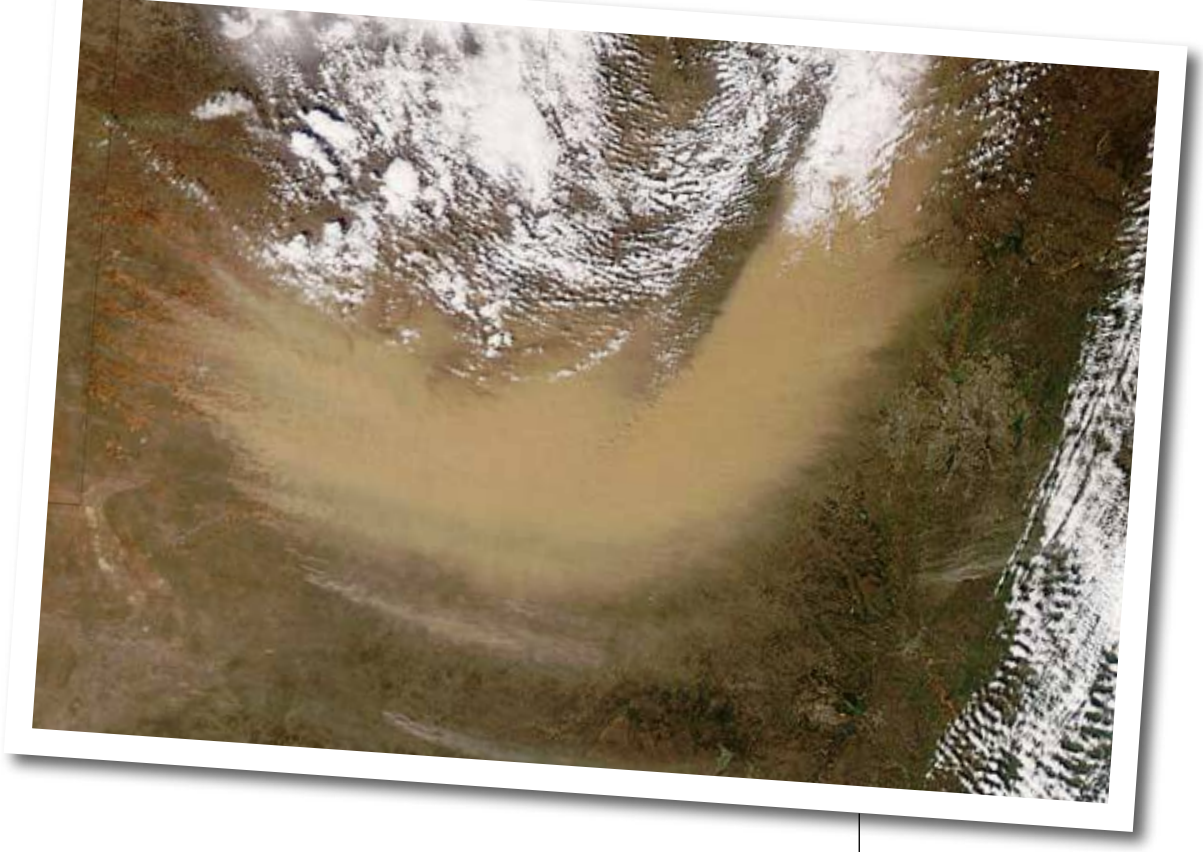
Bishop's research points out one critical aspect of dust storms in relation to our global climate. Dust storms move soil and sand over large distances, and that material impacts local weather conditions and the biosphere. Dust storms also influence global climate, and climate changes impact the frequency and severity of dust storms. Scientists do not fully understand how the two interact or the extent of those interactions.

The Intergovernmental Panel on Climate Change (IPCC) predicts in its Climate Change 2007 report that some regions around the world will experience hotter and drier weather, and therefore, more droughts. Such weather will begin or increase desertification, causing vegetation loss. Such loss exposes more soil to wind erosion, which increases the likelihood of dust storms. Recent analysis of dust-storm events shows such storms increasing in parts of the world, including Asian deserts and Africa's Sahara.

Dust in the atmosphere reduces the strength of sunlight reaching Earth's surface. This doesn't surprise veterans of the Dust Bowl years, nor those caught in dust storms today.

Most sunlight reductions are local and short-term. However, large dust storms, such as those produced by the 2001 Asian dust cloud, push small dust particles high into the atmosphere, where they remain for extended periods. These particles reflect sunlight back into space.

Scientists are well aware that stratospheric dust and particles from large volcanic eruptions cause reduced solar radiation at Earth's surface. Global cooling is the result. They speculate massive quantities of wind-driven dust could have the same impact. On the other



NORTHERN TEXAS disappears beneath a blanket of high winds February 24, 2007, in this MODIS satellite image. The storm had wind gusts up to 70 mph (113 km/hr), which downed power lines and knocked out electricity to 37,000 homes and businesses.

NASA/GSFC/JEFF SCHMALTZ (MODIS RAPID RESPONSE TEAM)

hand, dust may absorb some solar radiation and warm the local atmosphere. Whether dust impacts Earth on a global scale depends both on the composition and concentration of dust, and where it resides in the atmosphere.

More dust, less rain

Dust also plays a role in forming precipitation, or rain. Dust particles serve as condensation nuclei for water vapor. However, in high concentrations, dust particles may inhibit rainfall by offering too many sites to which water vapor may attach. According to scientists from Israel's Hebrew University and the Weizmann Institute, windblown desert dust can stifle rain clouds, reducing rainfall hundreds of miles away. As more dust interacts with the clouds, smaller raindrops form. These raindrops grow more slowly, and thus, yield less rainfall.

In concert with the raindrop-size reduction, heavy dust also reduces solar heating at Earth's surface. Reduced solar heating suppresses the convective activity that forms rain clouds, resulting in shallower clouds and less precipitation.

Aircraft and satellite observations, particularly those obtained with NASA's Tropical Rainfall Measuring Mission (TRMM) spacecraft, have confirmed this hypothesis. Data collected during a major North African dust storm in March 2000 showed clouds over the Atlantic Ocean in dust-filled air had smaller water-droplet sizes. Rain fell only from those clouds that formed in dust-free air, even though the clouds in dust-laden air contained a nearly equal amount of water.

A dusty future

The long-term outlook for our planet foretells a dusty future compared with the last few centuries, as population and agricultural pressures combine with global climate changes. High-impact grazing and intense agricultural cultivation expose and disrupt topsoil, which increases the amount of dust. If the additional dust inhibits local rainfall, it could exacerbate drought conditions and cause further or continued desertification and more dust storms.

THE SAHARA AS DUST SOURCE

An international team of scientists led by Ilan Koren of the Weizmann Institute in Israel has determined that approximately 40 million tons (36.3 million metric tons) of dust reach the Amazon basin from the Sahara Desert annually. And surprisingly, about half of that dust originates from a single, relatively small source: the Bodélé depression located northeast of Lake Chad in Chad. — *K. H.*

All thunderstorms are not created equal.

Run-of-the-mill storms, the kind humid air and warm temperatures brew by the dozen every summer day, form and dissipate within an hour. They're the sprinters in the world of convective weather.

Rarely, however, under just the right conditions, one of these sprinters becomes so organized it can run a marathon. Such storms, called supercells, may persist for hours as they churn out some of Earth's most dangerous weather, including heavy rain, hail, frequent lightning, and damaging winds — not to mention most of the tornados in the United States.

When thunderstorms turn DEADLY

Notoriously quick tempered, a supercell thunderstorm can go from docile to destructive in a few sweeps of a radar beam.

By Francis Reddy

A mature supercell releases the energy of a Nagasaki nuclear bomb, equivalent to 20,000 tons of high explosive, each second. That's about 100 times the energy released by an ordinary thunderstorm.

A supercell's interaction with its environment can sustain it for hours, split it in two, or quickly morph it from a weakening state to a deadly threat for anyone unlucky enough to be in its way. Thanks to satellites, radar, and other instruments, forecasters can issue warnings for conditions that may favor supercell growth. But once such storms materialize, their

A POWERFUL THUNDERSTORM, its contours highlighted by the setting Sun, builds up near Bloemfontein, South Africa, in February 2005. Under the right conditions, a storm like this can mature into a supercell capable of producing severe weather for hours. HANNES PIETERSE

IN THE LATE AFTERNOON and early evening of April 3, 2004, this supercell dropped golf-ball-sized hail that accumulated to 1 foot (30 cm) deep at Chaparral, New Mexico. The storm's anvil spreads into oncoming upper-level winds, a phenomenon called back-shearing. A storm with a back-sheared anvil contains a vigorous updraft. GREG LUNDEEN/NOAA

penchant for rapid intensity changes means meteorologists must keep close tabs on them.

Recipe for a supercell

Making a thunderstorm requires warm, moist, rising air near the surface and relatively cold, dry air aloft. Ordinary, or "air mass," thunderstorms can't maintain the rising column of warm, moist air that provides them with energy.

"You get an initial pulse upward," explains Steve Zubrick, a meteorologist at the National Weather Service's (NWS) Baltimore-Washington Weather Forecast Office in Sterling, Virginia. "The storm forms rain and radar reflectivity aloft, it can separate charge and start throwing out lightning bolts — and then the storm has no ability to continue its life. It rains back on its updraft, kills it, and dies out."

Making a supercell requires a few additional ingredients, says Harold Brooks at the National Severe Storms Laboratory (NSSL) in Norman, Oklahoma. "To make a supercell, you want the winds to increase in speed from the surface to 4 miles [6 kilometers] or more aloft and to change direction with height, typically from the south at low levels and the west aloft." This veering wind profile gives a supercell one of its defining characteristics: a rotating updraft.

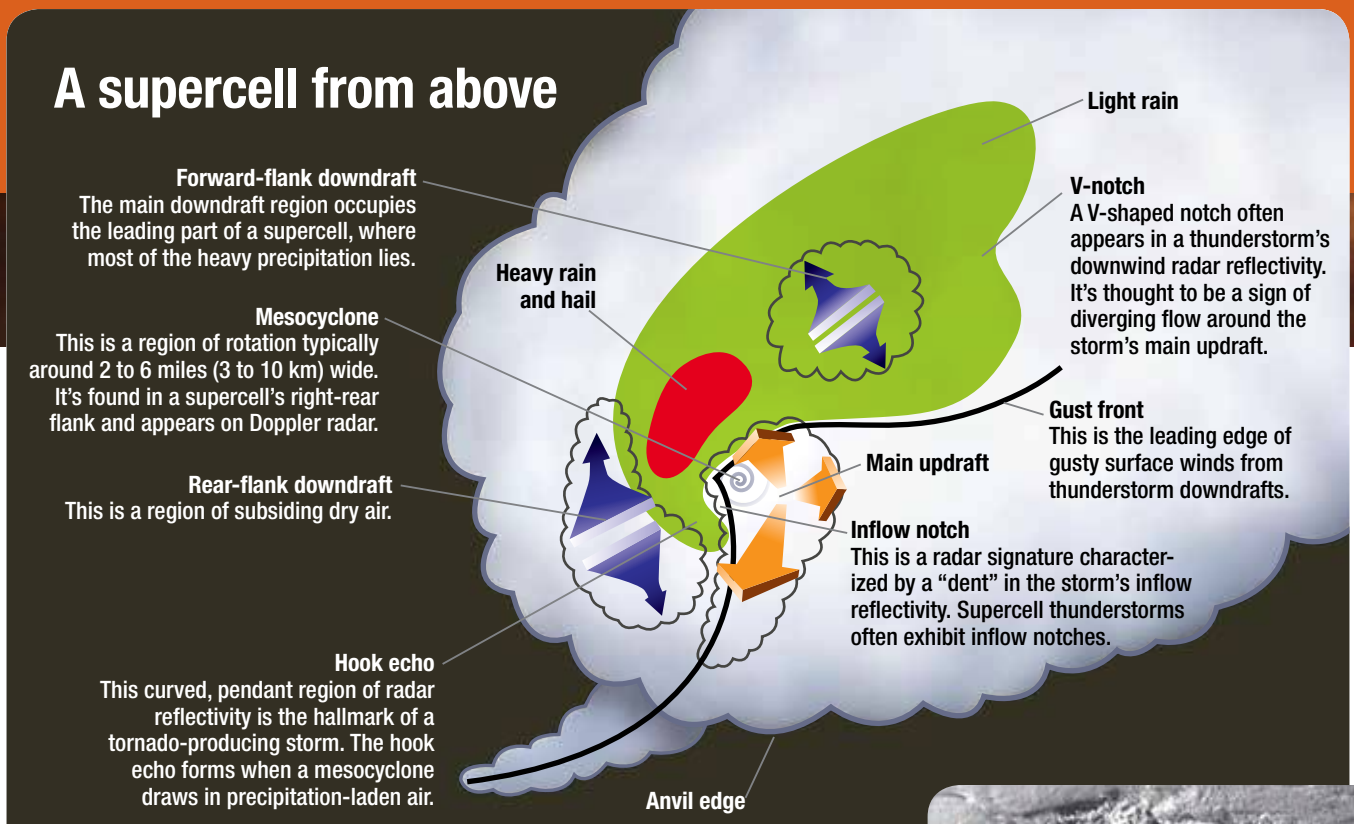
The NWS Storm Prediction Center, also in Norman, analyzes various data — from satellite and ground observations to numerical weather-prediction models — to understand the locations where these conditions will occur. Forecasters will map out areas with slight, moderate, and severe risks. "The slight, moderate, and high-risk zones represent how many severe weather reports they expect to see in those areas," Zubrick says.

"There are two levels of forecasting that are important," Brooks explains.

> A supercell's rapid changes pose problems for forecasts even an hour ahead.

"Several hours to a day ahead — the 'tornado watch' period — the biggest question frequently is whether a storm will get initiated. Up to about 1 hour ahead — the 'tornado warning' period — the speed at which the storm evolves is a problem."

A supercell can spawn a tornado in moments without giving clear signals it's about to do so. In the 1990s, as part of a


A supercell from above
Forward-flank downdraft
The main downdraft region occupies the leading part of a supercell, where most of the heavy precipitation lies.
Mesocyclone
This is a region of rotation typically around 2 to 6 miles (3 to 10 km) wide. It's found in a supercell's right-rear flank and appears on Doppler radar.
Rear-flank downdraft
This is a region of subsiding dry air.
Hook echo
This curved, pendant region of radar reflectivity is the hallmark of a tornado-producing storm. The hook echo forms when a mesocyclone draws in precipitation-laden air.
Heavy rain and hail
Light rain
V-notch
A V-shaped notch often appears in a thunderstorm's downwind radar reflectivity. It's thought to be a sign of diverging flow around the storm's main updraft.
Gust front
This is the leading edge of gusty surface winds from thunderstorm downdrafts.
Main updraft
Inflow notch
This is a radar signature characterized by a "dent" in the storm's inflow reflectivity. Supercell thunderstorms often exhibit inflow notches.
Anvil edge

SATELLITES AND GROUND RADARS see supercells from different perspectives. Green and red regions highlight radar reflectivity from areas with strong precipitation. Other radar reflectivity features include the V-notch and the inflow notch — both related to air flowing through the storm. The mesocyclone, a supercell's rotating core, appears on Doppler radar, which measures precipitation's radial speed. *EXTREME WEATHER:* ROEN KELLY

$4.5 billion modernization effort, the NWS deployed Weather Surveillance Radar-1988 Doppler (WSR-88D), better known as NEXRAD. A weather radar sends out radio waves from an antenna. Airborne particles, such as raindrops, snow pellets, and hailstones reflect some of these waves back to the antenna. Computers then convert these signals into images showing the locations and intensities of precipitation.

Doppler radars also measure the frequency changes in returning radio waves. Waves bounced off of an object moving away from the antenna lower the returned signal's frequency, while waves from an object moving toward the antenna raise the frequency. Studies show these radars significantly improve the quality of tornado warnings and lower the number of tornado casualties nationwide. In 1986, the average tornado-warning lead time was just 5 minutes; now, it's more than 15.

Even Doppler radars, which can detect the swirling signature of a growing tornado, have their limitations. "The radar can't see close to the ground, in most cases," Brooks says. "And it doesn't provide complete detail even when it does see close to the ground. In the absence of ground truth, it's really hard to know what's happening."

Trained storm spotters provide a valuable reality check, telling forecasters whether a storm is actually producing tornados and, if it is, pinpointing the twisters' locations. SKYWARN is a national network of volunteer spotters trained by local NWS offices. Combined with radar and satellite data, such reports help verify weather warnings and determine what the storms will do next.

Inside a supercell

A supercell is like other thunderstorms, only more so. Energy provided by the condensation of water vapor in moist air powers the growing storm. The cumulonimbus cloud rises to the stratosphere, where a temperature inversion prevents

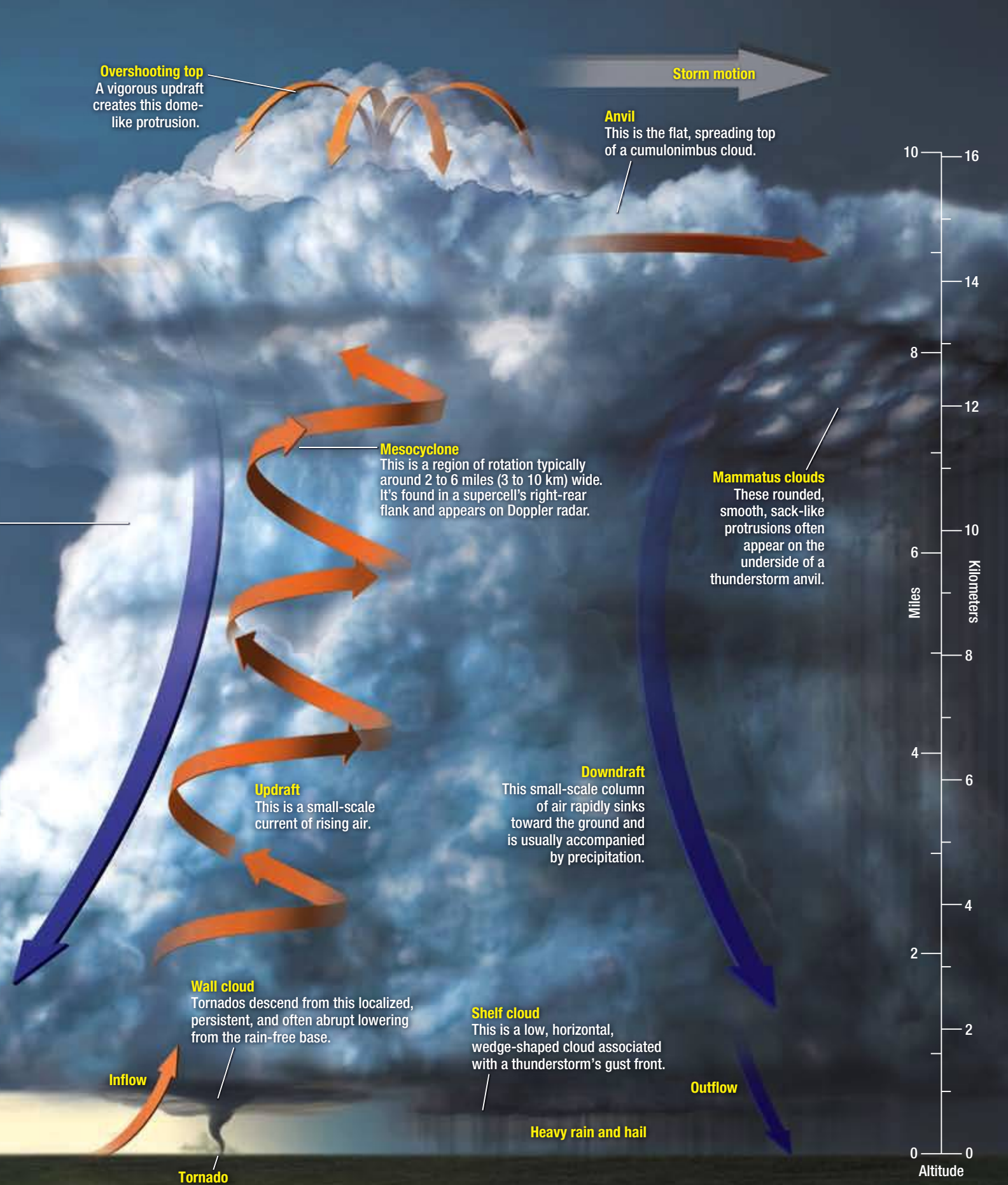
Continued on page 58

ON JUNE 19, 2001, at 8:50 P.M. EDT, the NOAA-15 satellite imaged a supercell straddling the Minnesota-Wisconsin border. Twenty minutes later, the storm spawned an F3 tornado that swept into Siren, Wisconsin. The twister killed three residents and injured 16. It damaged 200 homes. NOAA/CIMMS

Anatomy of a classic supercell

A SUPERCELL releases the equivalent energy of 20,000 tons of TNT — the yield of a Nagasaki-sized nuclear bomb — each second. The supercell's organization prevents cool air and precipitation from squelching its strong, rotating updraft, which allows the storm to thrive for hours. This illustration shows the basic structure of a classic supercell and highlights visible features often associated with such storms. *EXTREME WEATHER:* ROEN KELLY

Back-sheared anvil
The portion of a storm's anvil top that expands upwind.
Rotation
Rotation is the hallmark of a supercell. A storm's overall cylindrical appearance can be one visual clue that it's rotating. Others include cloud bands wrapping around the storm's outside edges or a flared cloud base. Doppler weather radars can detect storm rotation.
Flanking line
Cumulus or towering cumulus clouds connect to and extend outward from a supercell's most active part, normally on the southwest side. The tallest clouds usually occur closest to the storm.
Scud
These small, ragged, low clouds often are associated with a thunderstorm's cool, moist outflow.
Rain-free base
This dark, horizontal cloud base has no visible precipitation beneath it and typically marks the location of a thunderstorm updraft.


Overshooting top
A vigorous updraft creates this dome-like protrusion.
Storm motion
Anvil
This is the flat, spreading top of a cumulonimbus cloud.
Mesocyclone
This is a region of rotation typically around 2 to 6 miles (3 to 10 km) wide. It's found in a supercell's right-rear flank and appears on Doppler radar.
Mammatus clouds
These rounded, smooth, sack-like protrusions often appear on the underside of a thunderstorm anvil.
Updraft
This is a small-scale current of rising air.
Downdraft
This small-scale column of air rapidly sinks toward the ground and is usually accompanied by precipitation.
Wall cloud
Tornados descend from this localized, persistent, and often abrupt lowering from the rain-free base.
Shelf cloud
This is a low, horizontal, wedge-shaped cloud associated with a thunderstorm's gust front.
Inflow
Outflow
Heavy rain and hail
Tornado
A violently rotating column of air with circulation reaching the ground.
10
16
14
8
12
10
6
Miles
Kilometers
8
4
6
4
2
2
0
0
Altitude

April 28, 2002: A killer tornado tracks through Maryland

Washington
30 miles (48 km)
Indian Head
210
Marbury
Dumfries
Rison
La Plata
7:02 P.M. The National Weather Service's Baltimore/Washington forecast office issues a tornado warning for Charles and Calvert counties in Maryland.
7:02 to 7:07 P.M. Both tornados cross the heart of La Plata and cause widespread F2-F3 damage. Destruction in a one-square-block area on the city's east side is the most severe and rated F4. The secondary vortex dissipates.
7:30 P.M. The tornado crosses into Calvert County, Maryland. It destroys 10 homes and damages another 125.
6:45 P.M. EDT. An apparently weakening supercell re-intensifies as it crosses the Potomac River. It forms a new updraft core that will shortly produce a tornado.
6:57 to 7:01 P.M. The tornado grows stronger as it approaches La Plata, Maryland. Two subdivisions west of town receive F3-level damage. A second, weaker tornado briefly forms.
CHARLES COUNTY
Newmarket
CALVERT COUNTY
Patuxent River
7:15 P.M. Several thousand homes are damaged and at least 17,000 are without electricity.
6:56 P.M. The La Plata tornado first touches down south of Marbury in western Charles County, Maryland.
301
MARYLAND
VIRGINIA
Potomac River

A BRIGHT SWATH of damage runs through downtown La Plata, Maryland, 3 days after the city's F4 twister. NASA's EO-1 satellite imaged the area May 1, 2002. LAWRENCE ONG/EO-1 MISSION SCIENCE OFFICE/NASA/GSFC

Continued from page 55

it from rising much farther. Seen from a weather satellite, the storm's upper cloud expands radially, like pancake batter poured onto a frying pan.

The flat top gives the storm the classic anvil shape associated with thunderstorms. Upper-level winds usually stream the anvil cloud back so it leads the storm's forward motion. But if the updraft is unusually strong, as in a supercell, the anvil may expand into the upper winds — a phenomenon called back-shearing.

A cloud turret rises above the anvil. The updraft's sheer momentum carries the rising air a little higher into the stratosphere, which creates what meteorologists call an overshooting top. On visible satellite imagery, overshooting tops can cast obvious shadows when the Sun lies at a low angle.

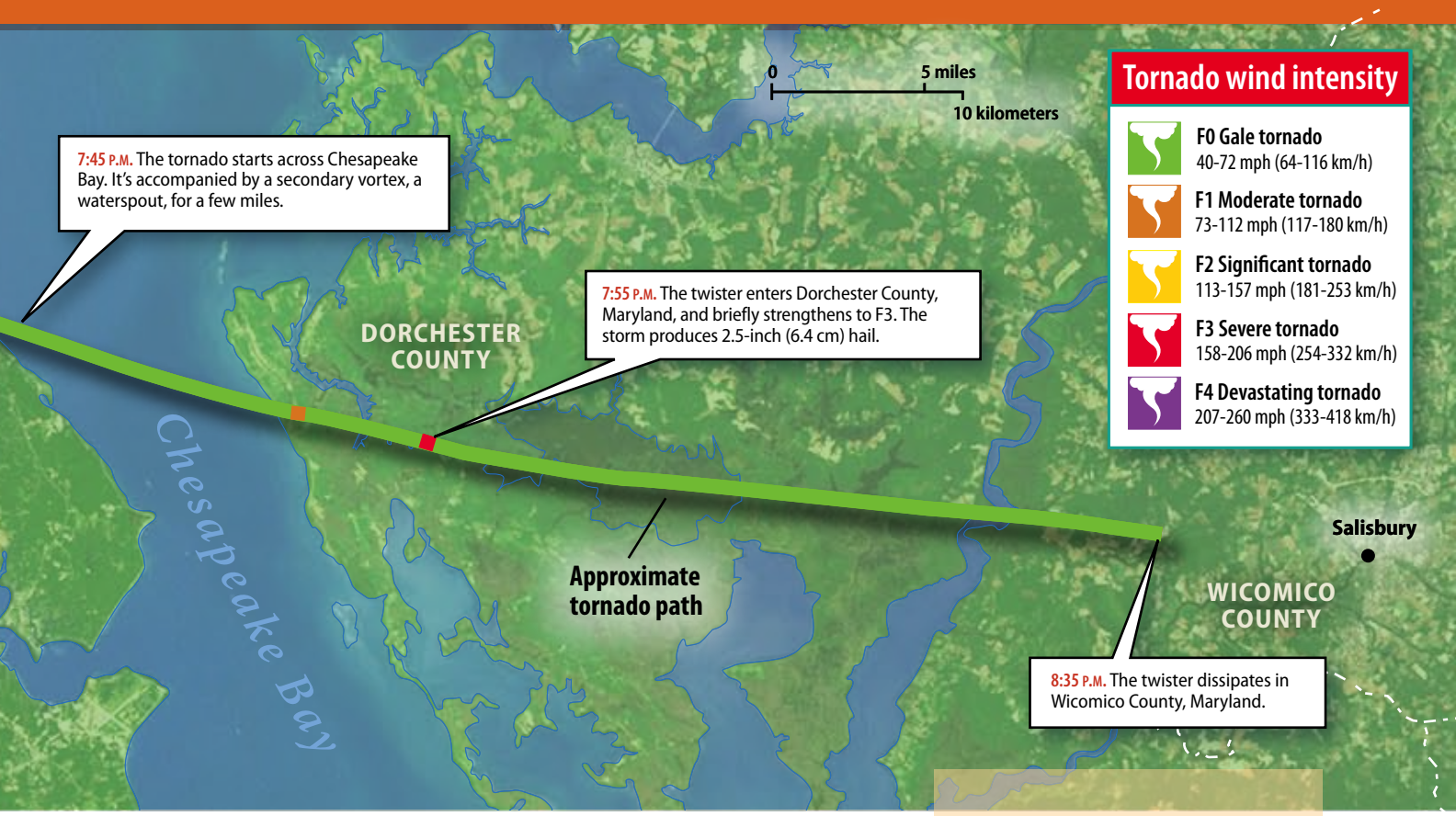
When displayed using only the strength of the reflected radar signal, supercells resemble a "flying V," says Zubrick. "Sometimes they look like crab claws. Sometimes they look like scorpions — the V parts are like little pinchers." Radar reflectivity shows precipitation. Near the edge of the storm, raindrop-laden air is forced to flow around the vigorous updraft. "The updraft remains rain-free as long as it's strong and continuous," he says. Because the updraft is almost impervious to rain, it forms an obstacle to air flow that results in a so-called V-notch. This is an indentation in the leading edge of a storm's rainfall.

The inflow notch and the hook echo are two other important radar-reflectivity features. "The inflow notch represents a rain-free area of the storm that's experiencing a good inflow of air into the updraft region," Zubrick explains.

The hook echo is a pendant, arc-like radar signature formed by precipitation that wraps around a supercell's mesocyclone — the rotating core that can spawn a tornado. A hook echo is a hallmark of a storm's tornadic potential. "The hook you see is the downdraft curling around the updraft core," Zubrick says.

The La Plata supercell

The supercell that produced a rare tornado at La Plata, Maryland, April 28,


0
5 miles
10 kilometers
Tornado wind intensity
F0 Gale tornado
40-72 mph (64-116 km/h)
F1 Moderate tornado
73-112 mph (117-180 km/h)
F2 Significant tornado
113-157 mph (181-253 km/h)
F3 Severe tornado
158-206 mph (254-332 km/h)
F4 Devastating tornado
207-260 mph (333-418 km/h)
7:45 P.M. The tornado starts across Chesapeake Bay. It's accompanied by a secondary vortex, a waterspout, for a few miles.
7:55 P.M. The twister enters Dorchester County, Maryland, and briefly strengthens to F3. The storm produces 2.5-inch (6.4 cm) hail.
DORCHESTER COUNTY
Chesapeake Bay
Approximate tornado path
Salisbury
WICOMICO COUNTY
8:35 P.M. The twister dissipates in Wicomico County, Maryland.

AN F4 TORNADO — the strongest ever to hit southeastern Maryland — carved a 68-mile (109 km) path across the state Sunday evening, April 28, 2002. Hardest hit was downtown La Plata, where 344 homes and businesses were destroyed. The twister's full toll includes $125 million in property damage, 122 injuries, and three deaths. An F4 rating equates to peak wind gusts between 207 and 260 mph (333 and 418 km/h). Only six recorded tornados this strong have occurred farther north or east.

EXTREME WEATHER: JAY SMITH

2002, offers a glimpse at how demanding it is to track such a storm and predict what it will do.

On that day, a strong upper-level trough — an elongated area of low atmospheric pressure — moved briskly from the Ohio Valley to the Middle-Atlantic coast. Associated with the trough were jet-stream winds greater than 90 mph (145 km/h), which proved conducive to the development of supercells.

The La Plata storm began life as a shower on the Kentucky/West Virginia border around 1:15 P.M. Over the next 45 minutes, the shower grew into a supercell — and then split in two.

"One of the features of a supercell storm is that it can have a split personality," says Zubrick. "It will split and produce what we call a right-mover and a left-mover." These are separate, oppositely rotating supercells that move left and right relative to the environment's prevailing wind.

"A lot of times, the environment will favor the right-mover, so that will become the predominant cell you see on radar," Zubrick explains. "You'll see the left-mover turn into nothing on radar in 10 to 15 minutes."

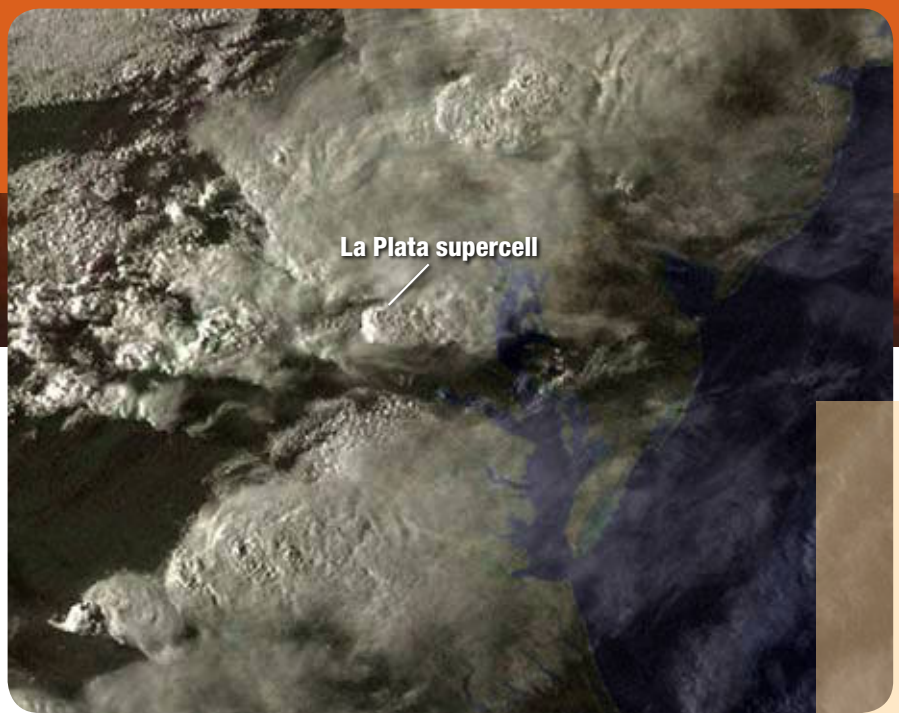
The right-mover tracked from eastern West Virginia into northwest Virginia and encountered a favorable environment. At 4:37 P.M., Zubrick's forecast office issued a tornado warning for Shenandoah County, Virginia. Eighteen minutes later, the supercell produced a short-lived F2 tornado south of Mount Jackson. The twister destroyed three houses and 19 barns, and damaged 27 other residences.

The Baltimore-Washington Weather Forecast Office issued subsequent tornado warnings as the storm tracked across northern Virginia through 6:45 P.M., but no additional twisters occurred. Given what was to come, this was a bit puzzling.

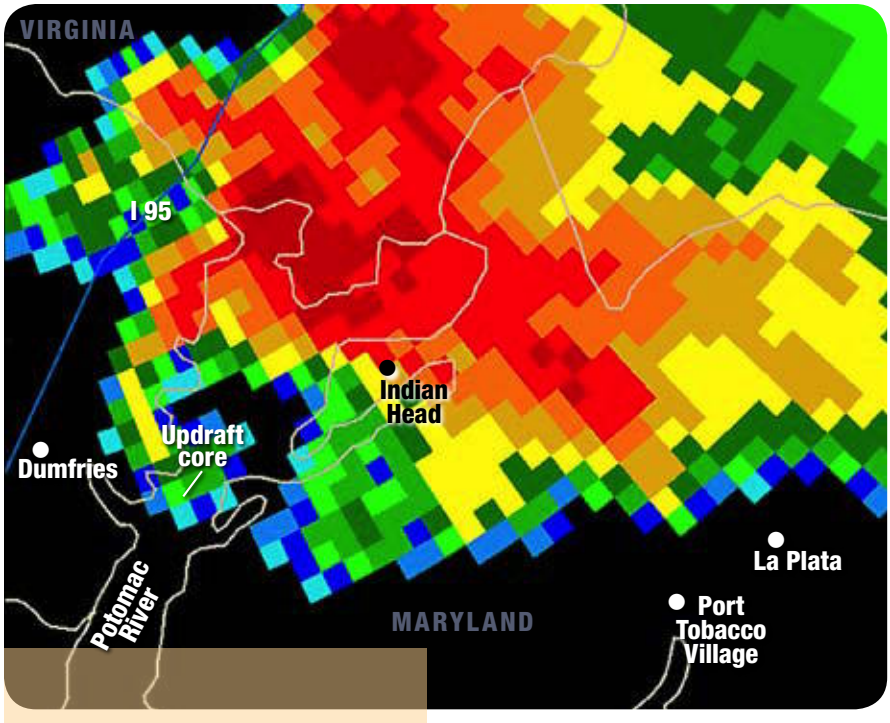
"It was going over sparsely populated areas," Zubrick notes. "But even afterward, we couldn't find any damage. So it wasn't like this thing was a bulldozer that was just marching across the landscape. The one spotter we had on the storm said it was really nothing."

The storm retained its supercell characteristics, but its mesocyclone fluctuated in size and intensity. "The downdraft can cut off the circulation of moisture-rich air to the updraft, and then that will kill the storm. That happens quite frequently," Zubrick notes. Like throttling back an engine, this causes the storm to lose intensity. "That cyclic nature comes from the continual creation and demise of new updrafts and downdrafts," he says.

At 6:45 P.M., the supercell approached the Potomac River. Without a confirmed



THE GOES-EAST SATELLITE captured this visible-light image at 6:45 P.M. EDT April 28, 2002. Storms appear in Maryland, Virginia, and Pennsylvania. The supercell that would strike La Plata, Maryland, is poised to cross the Potomac River. As the seemingly waning storm crossed the river, it re-intensified and spawned a deadly tornado. NOAA/CIMMS



THE NEXRAD RADAR at the Sterling, Virginia, NWS office caught the supercell as it formed a new updraft core while crossing the Potomac River, going east. This radar reflectivity view shows the storm within moments of the GOES-East image above. The new updraft eventually produced the La Plata, Maryland, tornado. STEVE ZUBRICK/NOAA/NWS

tornado report, and believing the storm's tornadic potential was decreasing, forecasters issued a severe thunderstorm warning for northern Charles and Calvert counties. "Severe thunderstorms can produce tornados with little or no advance warning," the alert read. In 10 minutes, that statement would prove literally true.

Exactly how and why a supercell initiates a tornado remains unknown. Robert Davies-Jones at the National Severe Storms Laboratory began his career in 1970 — before the first Doppler radar detection of a mesocyclone, the first 3-D computer simulations, and the first scientific storm chase. "By now, I thought we'd have solved the whole problem, but unfortunately we haven't," he says. "In the tornado business, you realize you can make up a rule one day, and the next day there's some counter-example that proves the exception. It's very frustrating that way."

Kick start

One question still unanswered is how changing terrain may influence a storm's behavior. The La Plata supercell came out of a hilly area near the Potomac River north of Dumfries, Virginia. It then crossed the river, which is just 1½ miles wide there. "We think, in the early spring, the winds may have been channeled up the river a little more intensely than over land," Zubrick suggests. The storm may have found a more hospitable environment once it moved over the water. "And then, somehow, that little impetus gave it a kick start, and it became very tornadic, very quickly," he says.

In the few minutes it took the storm to cross the Potomac, Zubrick's NEXRAD radar caught the formation of a new updraft. But spotter reports indicated nothing unusual, and the storm had more than an hour of non-tornadic behavior under its belt.

In addition, as the storm revved up, it began producing large hail. "We were

PASSENGERS ON A FLIGHT bound for Atlanta received a spectacular aerial view of the declining La Plata supercell. This picture shows the storm around 8 P.M. April 28, 2002. STEVE MACIEJEWSKI

getting some spurious data plotted in the radar that was due to hail contamination," Zubrick explains. This confused the computer logic that interpreted the radar's velocity data. This, in turn, caused NEXRAD's built-in Tornado Detection Algorithm to return false positives.

"We had a spotter on the west side of the river, and we were getting a hit there, and nothing was observed in the storm," Zubrick says. "Most radar operators do not rely on the algorithm. We're looking at all the radar data as it's coming in — in real time — on a storm, and we'll usually find those types of signatures before the algorithm goes off."

> The most severe damage, rated F4, occurred in a one-square-block area.

At 6:56 P.M., the thunderstorm lumbered across the Potomac River into Maryland, and the La Plata tornado touched down near Marbury. Six minutes later, forecasters issued a tornado warning for Charles and Calvert counties. At 7:10 P.M., the first of three fatalities occurred in La Plata.

The city's most severe damage, rated F4, occurred in a one-square-block area on the east side. There, a dense cloud of flying debris from a lumberyard ravaged structures. The twister was the most violent on record in Maryland. According to the NWS, only 1 percent of tornados become this intense. Only six tornados of similar strength have been recorded farther north or east.

The speed with which the La Plata supercell changed its personality from "nothing" to a supercharged killer impresses meteorologists. They're looking forward to a new suite of tools that could improve their knowledge of a supercell's changing strength and help them better predict its future behavior.

These include new technologies like orbital lightning mapping. By monitoring the frequency and location of a storm's electrical activity from space, next-generation weather satellites could give forecasters better insight into changes in a storm's intensity and track.

Another technology, called phased-array radar, could collect the same information as current Dopplers in about one-sixth the time. Rather than slew a dish to a target, a phased array system uses stationary antennae and instead sweeps electronic beams. Each beam can be targeted independently at particular elements of a storm. This would give forecasters more accurate and complete data than the current NEXRAD radars. In fact, researchers believe phased arrays could extend tornado-warning lead times to 22 minutes.

While supercells are rare and violent tempests, they're also quick-change artists that forecasters must monitor closely. Meteorologists welcome any innovation that improves researchers' insights into what powers and maintains these idiosyncratic and sometimes deadly storms.

Francis Reddy *is a senior editor of* Astronomy.

Where do the *fastest winds blow?*

Earth's rotation creates global winds, but local changes in atmospheric pressure can make them howl.

By Laura Baird

Differences in atmospheric pressure create wind. Extremely high and low air pressures go hand in hand with severe weather. When air is heated, particles spread out, and air rises. Colder, denser air takes its place in a phenomenon we feel as wind. The greater the pressure difference, the stronger the wind blows.

The standard sea-level pressure is 29.92 inches (759.97 millimeters) of mercury. This is the amount of mercury that would be supported by a theoretical column of air stretching from Earth's surface to the top of the atmosphere. The fastest winds occur where the pressure gradients are exaggerated, like inside a tornado or hurricane.

Because tornados destroy meteorological equipment, no one has directly measured wind speed inside a twister's core. Using Doppler radar, however, scientists remotely recorded a 302 mph wind (486 km/h) in the F5 tornado that hit Bridge Creek, Oklahoma, in spring 1999.

This far exceeds the fastest-moving surface wind, clocked atop New Hampshire's Mount Washington during an April 1934 storm: 231 mph (372 km/h). In this case, the summit was caught between a high-pressure system to its north and east, and falling pressures to the west.

Meteorologists don't have a set number separating high and low pressure. Low pressure means the air is rising and cooling off, which can form clouds and rain. High-pressure areas, on the other hand, suppress cloud development and generally mean a favorable local forecast.

At nearly 1.2 miles (1.9 kilometers) above sea level, Mount Washington is the highest point in the northeastern United States. The yearly mean wind speed is 35 mph (56 km/h). WILLIAM HEMMEL

World's strongest sustained surface wind
231 mph (372 km/h)
Mount Washington,
New Hampshire
April 12, 1934

World's strongest wind gust
207 mph (333 km/h)
Thule, Greenland
March 8, 1972

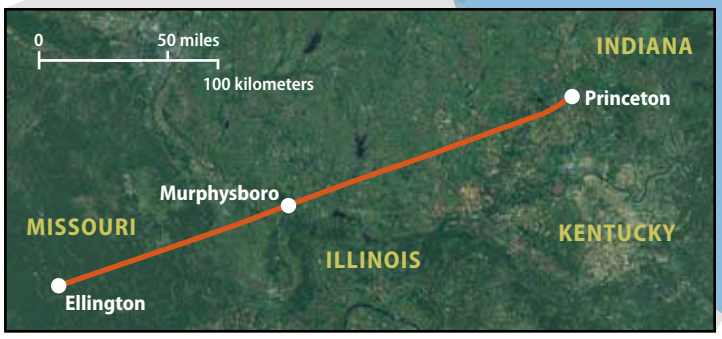
North America's highest sea-level air pressure
31.85 in. (808.99mm)
Northway, Alaska
January 31, 1989

World's widest tornado
2.5 miles (4 km)
Hallam, Nebraska
May 22, 2004

World's fastest wind speed recorded in a tornado
302 mph (486 km/h)
Bridge Creek, Oklahoma
May 3, 1999

Greatest distance traveled by a tornado
219 miles (352 km)
over 3.5 hours
Ellington, Missouri,
to Princeton, Indiana
March 18, 1925

North America's lowest sea-level air pressure (excluding tornados)
26.35 in. (669.29mm)
Matecumbe Key, Florida
September 2, 1935



This map shows the track of the 1925 tornado that leveled 15,000 homes and killed nearly 700 people. In Murphysboro, Illinois, 234 people died. NASA/WORLDWIND

Worldwide winds

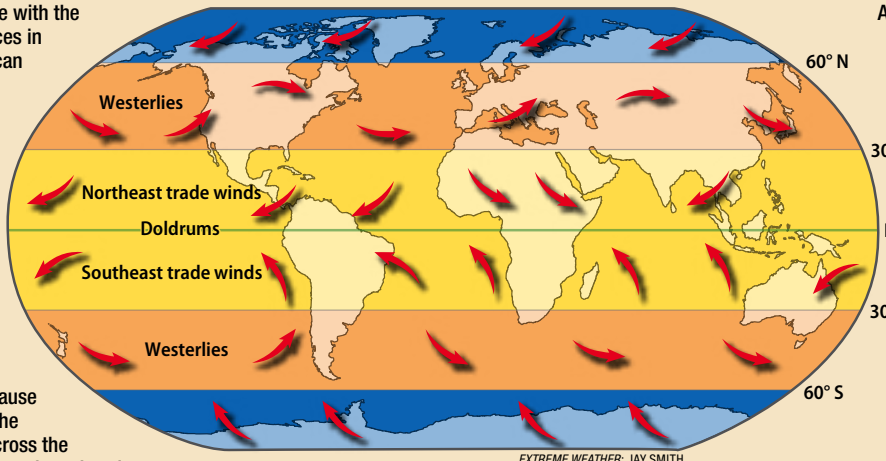
Temperature differences create variations, so hot equatorial regions experience lower air pressures, while the poles see higher air pressures. This inequality creates a global wind pattern as the atmosphere strives for equilibrium. — *L. B.*

THE NORTH AND SOUTH POLES:

Above 60° latitude, near each pole, cold air is deflected back toward the equator. Where the "polar easterlies" collide with the westerlies, drastic differences in temperature and pressure can produce extreme weather.

30° NORTH AND SOUTH LATITUDES:

Air heated at the equator spreads out toward the poles, cools off, and sinks again around 30° latitude. Most of the air flows back toward the equator, and Earth's rotation causes the air to flow toward the west. This movement creates the trade winds, so-named because seafaring Europeans used the strong, constant breeze to cross the Atlantic Ocean in search of goods and trade.



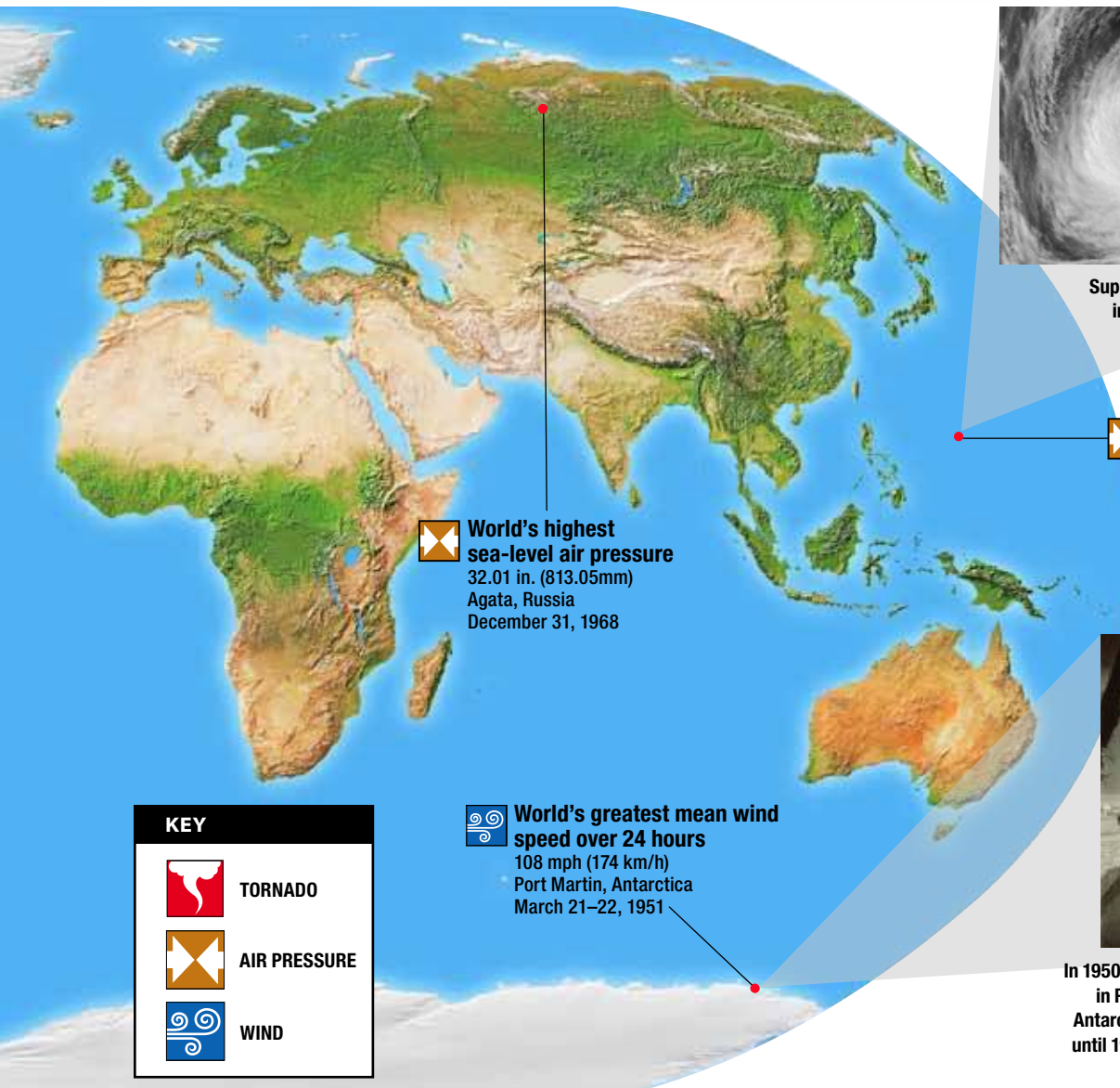
EXTREME WEATHER: JAY SMITH

THE EQUATOR:

The equator receives the most direct sunshine, which heats the air and causes it to rise. As the hot air expands, it releases its moisture and leaves low pressures behind. Few surface winds blow where the trade winds meet, a calm area nicknamed the "doldrums."

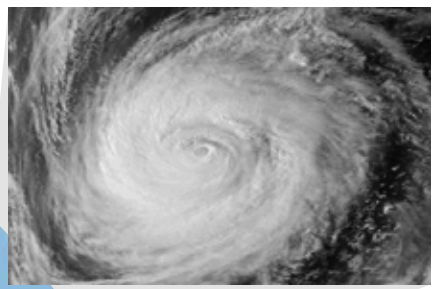
BETWEEN 30° AND 60° NORTH AND SOUTH LATITUDES:

Between 30° and 60° latitude, air flows toward the east due to the Coriolis effect, a deflecting force created by Earth's rotation. The large temperature gradient between these latitudes powers the prevailing "westerlies" in both hemispheres.



World's highest sea-level air pressure
32.01 in. (813.05mm)
Agata, Russia
December 31, 1968

World's greatest mean wind speed over 24 hours
108 mph (174 km/h)
Port Martin, Antarctica
March 21–22, 1951



Super Typhoon Tip reigns as the most intense tropical cyclone on record. It spanned some 1,350 miles (2,175 km), or nearly half the size of the United States. NOAA

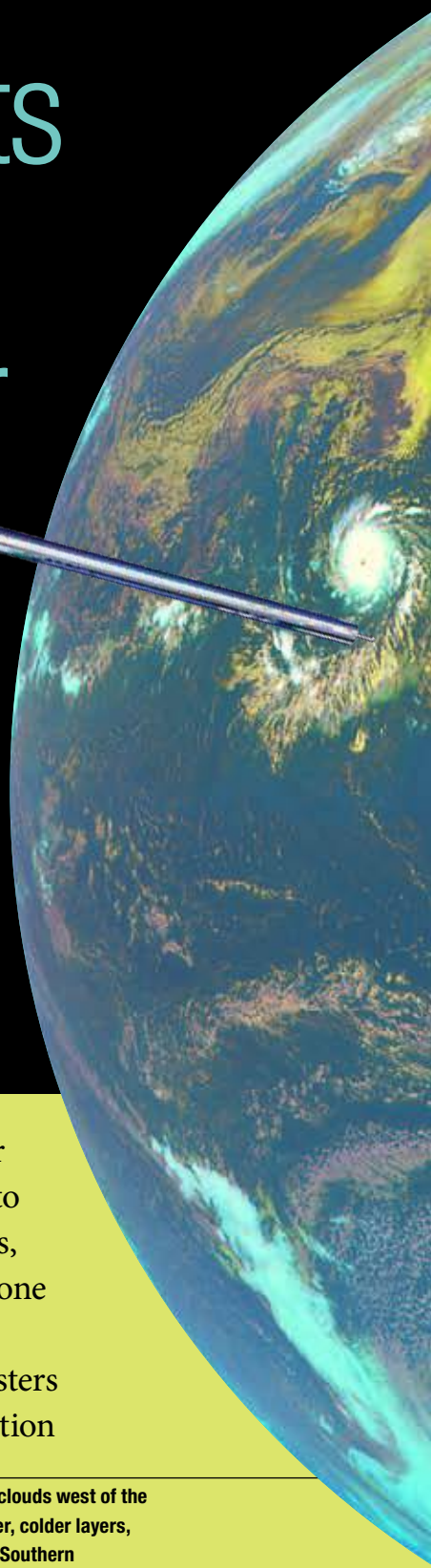
World's lowest sea-level air pressure (excluding tornados)
25.69 in. (652.53mm)
Eye of Typhoon Tip:
16°44'N, 137°46'E
October 12, 1979

In 1950, the *Commandant Charcot* docked in Port Martin, the first French base in Antarctica. The station housed 11 people until 1952, when it was destroyed by fire.

EXPÉDITION POLAIRES FRANÇAIS

NASA EARTH OBSERVATORY/FRANCIS REDDY/*EXTREME WEATHER:* JAY SMITH

How scientists track weather from space



Every day, satellites use visible light and infrared to show us weather from orbit. Here's how they do it.

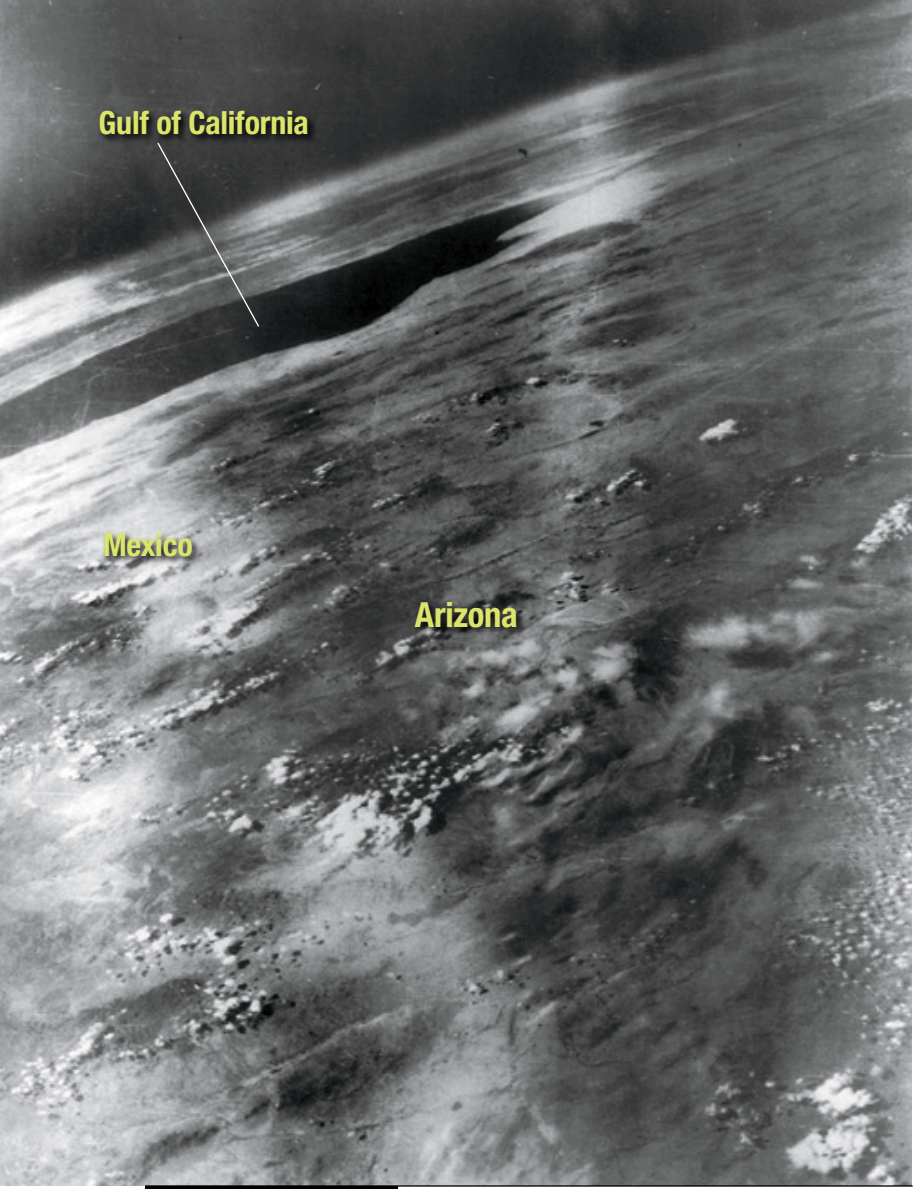
By Steven A. Ackerman

We take for granted the bird's-eye view of developing weather systems that satellites provide. Forecasters use the orbiters to monitor shifting weather systems, including thunderstorms, hurricanes, and extratropical cyclones. And, thanks to the web, anyone can access quality satellite images with just a few mouse clicks.

Satellite data help forecast the weather in two ways. Expert forecasters interpret the images; computer-based, or numerical, weather-prediction

GOES 13 (left), the most recently launched geostationary weather satellite in the U.S. fleet, returned a full-disk image of Earth (right) July 20, 2006. Tropical storm Beryl appears east of New England, while hurricane Daniel swirls in the Pacific, southwest of Baja California. The picture is a composite of visible and infrared data. Yellow clouds correspond to bright, lower, warmer layers, such as marine stratus clouds west of the Americas. Blue-green clouds are darker, higher, colder layers, such as the tops of great winter storms in the Southern Hemisphere. White clouds, such as midday thunderstorms over the Tropics, are both high (cold) and well lit by the Sun.

EARTH: GOES PROJECT, NASA/GSFC/NOAA; SPACECRAFT: BOEING CORP.



THE FIRST GLIMPSE of weather from space came in October 1946 — 11 years before the first satellite — courtesy of captured V-2 rockets launched from New Mexico's White Sands Missile Range. A V-2 launched March 7, 1947, returned this view of Arizona, northern Mexico, and the Gulf of California from 101 miles (162 km) up.

WHITE SANDS MISSILE RANGE/NAVAL RESEARCH LABORATORY

models assimilate observations. Image analysis plays an important role in short-term forecasts, those that predict the weather 1 to 3 hours into the future. Numerical weather predictions are more useful for forecasts from 12 hours to 3 days out.

While weather forecasters routinely analyze current satellite observations, most data never reach forecasters' eyes. Most satellite observations go directly into numerical models. In fact, today's weather-forecast models rely on satellite data more than any other weather observation. These data include the vertical distribution of temperature and humidity, ozone concentration, cloud distributions, land and sea surface temperatures, location of volcanic ash, lightning, and wind speeds and directions.

It's difficult to imagine how meteorologists worked before weather satellites existed. Observations from balloons, aircraft, and widely separated ground stations couldn't provide the detail needed to predict the tracks and changing strengths of powerful storms.

One way to appreciate satellite benefits is to look at similar storms that occurred before and after we developed current technologies. We'll take a close look at three notorious storms that rocked the Great Lakes region.

A deadly blizzard

The Armistice Day Storm ravaged the Upper Great Lakes region November 11 and 12, 1940. It began developing November 7, when a deep low-pressure system pushed onto Washington's Pacific coast.

Just 4 months earlier, the Tacoma Narrows Bridge spanning Puget Sound had opened to traffic. But on November 7, sustained 42 mph (67 km/h) winds set up such violent oscillations in the bridge's roadway that authorities decided to close it. At 11 A.M. Pacific Time, in a dramatic foreshadowing of this storm's ultimate toll, the Tacoma Narrows Bridge collapsed.

Two days later, the storm crossed the Rocky Mountains and intensified over the Colorado plains. On November 10, the massive system generated winds of 66 mph (106 km/h) in Amarillo, Texas, and 54 mph (87 km/h) in Oklahoma City. During the night, the storm intensified further and began to move northeast.

The next day, this powerful storm, traveling in excess of 50 mph (80 km/h), made its presence painfully known throughout the Upper Great Lakes. Chicago's temperature dropped from 63° to 20° Fahrenheit (17° to –7° Celsius). On Lake Superior, the steamer *Crescent City* experienced winds so strong, automobiles were lifted off its deck and flung overboard. On Lake Michigan, 50-foot (15 meters) waves sank three steamers, killing 59.

In Wisconsin, Minnesota, and Iowa, duck hunters were caught unprepared for the rapid weather change. Some survived by overturning their skiffs and crawling underneath for protection; many others froze to death. By the time the Armistice Day Storm ended, it had killed more than 150 people, sunk at least 3 ships, downed a plane, stranded hundreds of train passengers, killed more than 2 million turkeys, and isolated Midwestern towns with 20-foot (6.1m) snow drifts.

Twenty years earlier, meteorologists had recognized these types of winter storms through careful observations

The 1940 Armistice Day gale sank three ships and killed 150 people.

of changing weather conditions measured by instrumented ground stations. But ground-based observations are limited in scope.

Had satellite observations been available in 1940, forecasters and weather watchers would have seen the developing storm's force and understood how quickly it was descending on the Great Lakes. Timely warnings could have been issued and lives saved.

Satellite beginnings

The era of weather satellites began April 1, 1960, when the U.S. launched the first Television and InfraRed Observation Satellite (TIROS I). During its 2½ month life span, the satellite's cameras gave meteorologists their first consistent views of global cloud patterns. Nine TIROS research satellites followed. Launched in quick succession, the spacecraft tested new cameras and methods for transmitting data back to Earth.

By 1965, TIROS X proved that satellite observations could be an important tool for a national weather forecasting system. With TIROS X, forecasters could see global cloud patterns and how they moved. TIROS X images lacked the detail seen in today's satellite pictures, but these first views identified the location of hurricanes and tropical storms long before they could affect shorelines.

As groundbreaking as they were, the TIROS satellites were limited in key ways. Observations must be timely and consistently available to be useful to forecasters. The TIROS satellites circled Earth from North Pole to South Pole, which provided observations over the whole globe. But they flew over the United States only twice a day. American meteorologists realized they needed satellites in a different orbit, one that would provide timely observations over a large geographic region.

This need resulted in geostationary satellites. Satellites at altitudes of 22,300 miles (35,900 kilometers) circle Earth as fast as it turns, thus essentially hovering over a single point on the planet. This is called a geostationary orbit (abbreviated GEO).

A GEO satellite has a continuous, high-quality view of the tropics and middle latitudes, and it can track storm systems continuously by returning rapid image sequences. This capability allows weather forecasters to predict storm movement over short time periods — 30 minutes or less.

The age of GEO satellite weather pictures, the ones that now permeate daily weather reports, began with the December 6, 1966, launch of the first Applications Technology Satellite (ATS-1). Aboard ATS-1, a new instrument called a spin-scan camera made it possible to image the entire Western Hemisphere and routinely monitor weather-system movements. By 1967, ATS-3 provided the first full-color image of Earth from space.

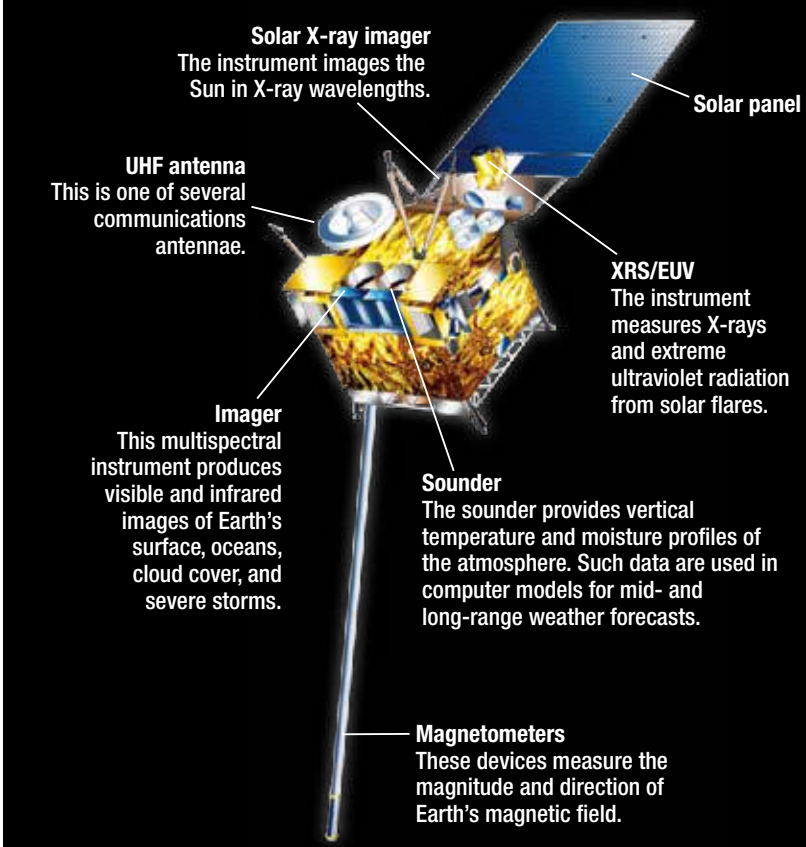
Two Synchronous Meteorological Satellites, launched in 1974 and 1975, paved the way for the U.S. Geostationary Operational Environment Satellite (GOES) program. GOES 1 launched October 16, 1975. GOES program satellites continue today as our primary weather eyes in the sky.

Gale of November

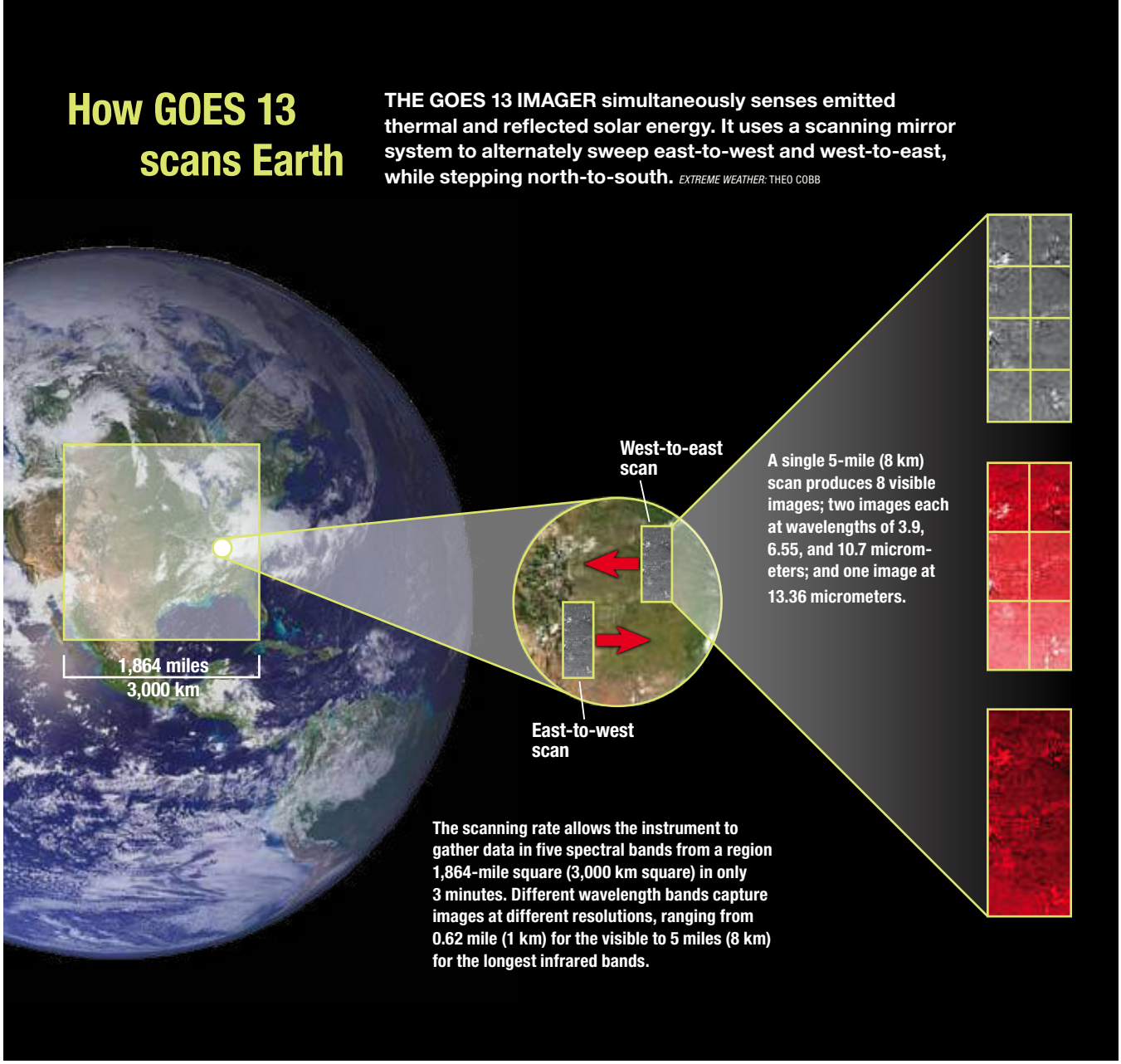
In November 1975, less than one month after GOES 1's launch, a storm developed that was a near repeat of the 1940 Armistice Day Storm. Thanks to geostationary satellites, computers, and improved communications, forecasts would fare better than they did in 1940. But this storm, too, had deadly consequences. It sent the freighter *SS Edmund Fitzgerald* to the

Steven A. Ackerman *is the director of the Cooperative Institute of Meteorological Satellite Studies at the University of Wisconsin-Madison's Space Science and Engineering Center.*

GOES 13's anatomy


Solar X-ray imager
The instrument images the Sun in X-ray wavelengths.
Solar panel
UHF antenna
This is one of several communications antennae.
XRS/EUV
The instrument measures X-rays and extreme ultraviolet radiation from solar flares.
Imager
This multispectral instrument produces visible and infrared images of Earth's surface, oceans, cloud cover, and severe storms.
Sounder
The sounder provides vertical temperature and moisture profiles of the atmosphere. Such data are used in computer models for mid- and long-range weather forecasts.
Magnetometers
These devices measure the magnitude and direction of Earth's magnetic field.

THE LATEST GENERATION of geostationary weather satellites comes equipped with sophisticated instruments to image and profile Earth's weather in multiple wavelengths, detect variations in Earth's magnetic field, and monitor solar activity. *EXTREME WEATHER:* THEO COBB


How GOES 13 scans Earth
THE GOES 13 IMAGER simultaneously senses emitted thermal and reflected solar energy. It uses a scanning mirror system to alternately sweep east-to-west and west-to-east, while stepping north-to-south. EXTREME WEATHER: THEO COBB
West-to-east scan
A single 5-mile (8 km) scan produces 8 visible images; two images each at wavelengths of 3.9, 6.55, and 10.7 micrometers; and one image at 13.36 micrometers.
1,864 miles
3,000 km
East-to-west scan
The scanning rate allows the instrument to gather data in five spectral bands from a region 1,864-mile square (3,000 km square) in only 3 minutes. Different wavelength bands capture images at different resolutions, ranging from 0.62 mile (1 km) for the visible to 5 miles (8 km) for the longest infrared bands.

bottom of Lake Superior with all 29 hands. Gordon Lightfoot's 1976 ballad "The Wreck of the Edmund Fitzgerald" helped make this incident the most famous disaster in Great Lakes shipping history.

On November 8, a low-pressure system with the makings of a classic November extratropical cyclone developed over the Great Plains. On November 9, the *Edmund Fitzgerald*, one of the largest freighters on the Great Lakes, departed Superior, Wisconsin, with 26,116 tons of taconite bound for a steel plant on Zug Island, near Detroit. Shortly after leaving port, the *Fitzgerald* made contact with the *SS Arthur M. Anderson*, which was headed on a similar route, and the two vessels traveled together.

Guided by computer models, the National Weather Service (NWS) predicted the storm would move toward the Great Lakes and pass just south of Lake Superior. The NWS issued a gale warning for Lake Superior at 7 P.M. EST November 9. This meant forecasters expected maximum sustained wind speeds to reach 39 to 46 mph (63 to 74 km/h). The NWS predicted east to northeasterly winds during the night, with winds shifting northwest to north by the next afternoon.

Forecasters used surface observations of wind and pressure and satellite images to monitor the storm's strength and position. At approximately 10:40 P.M., the NWS revised its forecast for eastern Lake Superior to easterly winds becoming southeasterly the morning of November 10. By 2 A.M. that morning, NWS forecasters upgraded the gale warning to a storm warning. They predicted northeast winds becoming northwesterly and wave heights from 8 to 15 feet (2.4 to 4.6m).

At about this time, the captains of the *Anderson* and the *Fitzgerald* discussed the threatening weather and decided to change their route. The safer course would take them northward, where Canada's coast

In 1975, hurricane-force winds knocked out a Lake Superior lighthouse and whipped up monster waves.

would shelter them from storm-generated waves.

But satellite images showed the storm tracking farther north than originally predicted; at 7 A.M. it passed over Marquette, Michigan, and started across eastern Lake Superior. Because of this, the strongest winds would come out of the northwest, blowing steadily over the length of Lake Superior and building up large waves.

The captains' decision to hug the Canadian coast would have protected them from the forecast conditions, but, with the storm's actual track, *Anderson* and *Fitzgerald* were in greater peril. By the time the storm reached the Great Lakes, the ships were too far in their journey to change course again.

By 2:45 P.M. November 10, northwesterly winds blew steadily at 48 mph (78 km/h), generating waves up to 16 feet (4.8m) high. At 3:30 P.M., *Fitzgerald*'s captain, Earnest McSorely, radioed the *Anderson* to report his ship had received topside damage, was taking on water, and had developed a list.

At 4 P.M., an estimated 86 mph (139 km/h), hurricane-force, northwest gust struck the *Anderson*. The same gust knocked out the lighthouse and radio beacon at Whitefish Point in Michigan's Upper Peninsula.

Shortly after that, McSorley radioed *Anderson* he had lost both of his radars — likely a result of wind damage — and he requested *Anderson* to monitor his position and course. *Fitzgerald* was now sailing blind, completely dependent on the *Anderson* for navigation.

At 7 P.M., two massive waves, estimated at 25 feet (7.6 m) or higher, smashed into the *Anderson*, which trailed the *Fitzgerald* by about 10 miles (16 kilometers). The waves were headed *Fitzgerald*'s way, but at 7:10 P.M. McSorley told the *Anderson*: "We are holding our own."

This was the doomed ship's last communication. Five minutes later, as a snow squall moved in, the *Anderson* lost the *Fitzgerald* on radar. Today, the ship lies broken in two 530 feet (162m) below the surface of Lake Superior.

The GOES era

In 1975, a single GOES satellite monitored the weather in visible and infrared wavelengths. Much has changed since then.

Today, the United States operates three geostationary satellites. GOES 10, stationed at longitude 60° West, monitors South America.

GOES 11, at longitude 135° West, monitors the U.S. West Coast and the Eastern Pacific.

GOES 12, at longitude 75° West, keeps watch on the U.S. Gulf and East coasts.

In fact, these satellites provide such valuable service that no one wants a hardware failure to interrupt it. So GOES 13, launched May 24, 2006, will remain on standby until one of the satellites now in use becomes decommissioned.

Frequent images allow forecasters to monitor changing weather patterns and thus update forecasts more quickly. Today, GOES satellites image the

Keeping a weather eye on hurricanes

Satellite observations improve forecasts for many weather systems, including hurricanes. Geostationary satellites can quickly identify hurricanes developing over warm tropical oceans and track the storms.

From the overall cloud pattern in satellite images, forecasters can estimate a hurricane's strength. Cloud movements help meteorologists understand a storm's upper-level winds.

But monitoring hurricane intensity takes more than GEO satellites. Polar orbiters fly closer to Earth, and their instruments can penetrate clouds that obscure detail from geostationary satellites. Let's take a look at two polar-orbiting missions.

Quick Scatterometer (QuikSCAT). QuikSCAT carries a high-frequency radar that allows it to monitor winds over the oceans. Winds over the sea cause small-scale sea-surface disturbances that change the reflected radar beam in a particular way. These changes depend on both wind speed and direction.

Because its radar beam penetrates clouds, QuickSCAT can measure winds during all kinds of weather. Hurricane winds are strongest at the ocean surface, so QuickSCAT's data provide a large-scale view of storm winds that ship and aircraft measurements cannot.

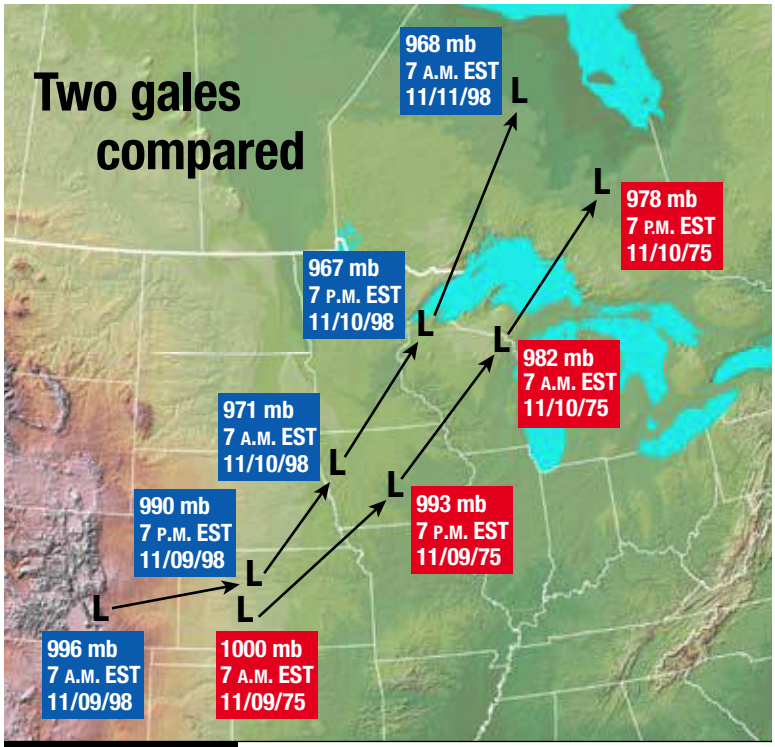
The data help pinpoint a hurricane's center by locating the eye's circular winds. In September 2006, QuikSCAT observations helped forecasters upgrade Helene from a tropical storm to a Category 2 hurricane.

Tropical Rainfall Measurement Mission (TRMM). This satellite measures precipitation over the tropical oceans. It provides information on individual storms' rain rates and gives meteorologists a global view of ocean precipitation.

TRMM carries an instrument that measures the small amount of microwave energy precipitation emits. This instrument penetrates a storm's upper-level clouds. Working in concert with TRMM's radar, this instrument lets forecasters map the structure of hurricane rain bands and the development of its central eye wall.

By observing storm precipitation, TRMM improves our understanding of how rainfall occurs, which, in turn, will lead to better hurricane predictions. Today, a 3-day tropical cyclone forecast is as accurate as a 2-day forecast made just a decade ago.

This improvement has direct benefits. Better predictions mean that hurricane watches and warnings apply to smaller regions, which improves evacuation planning. Predicting a hurricane's intensity at landfall remains an acute forecasting challenge. — *S. A. A.*



THIS PLOT SHOWS similarities in the tracks and strengths of the 1975 and 1998 Great Lakes November gales. Compare the dates, times, and central pressures (in millibars) of these systems. Better satellite data, tied with improved computer models, led to more accurate forecasts — and no fatalities — in 1998. *EXTREME WEATHER:* THEO COBB

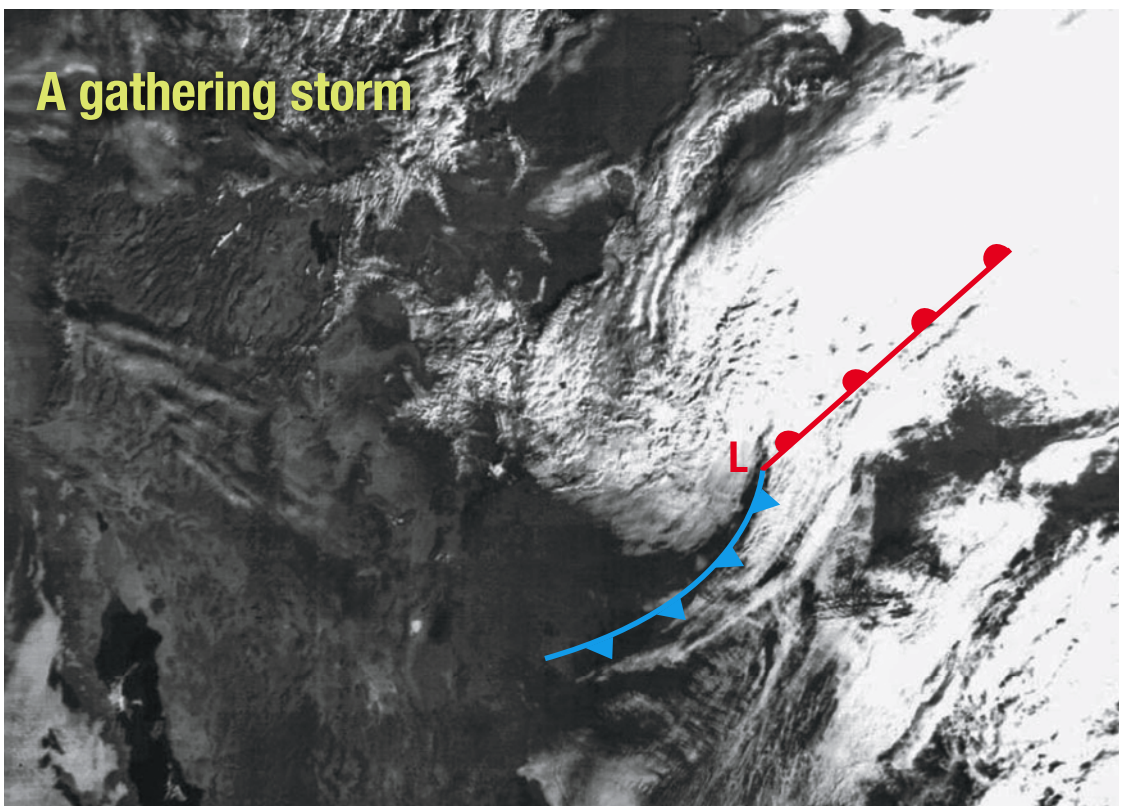
continental United States every 15 minutes. In severe weather conditions, the satellites can be placed in "super rapid scan" mode to view a particular storm every 30 seconds.

While early GEO satellites imaged in only two wavelengths, new models record five wavelengths. This provides forecasters with an enhanced view of fog and cloud movement, and a better determination of cloud altitudes. The imagers also provide improved spatial resolution. Visible-wavelength instruments can resolve weather systems down to 0.4 square mile (1 square km).

Storm warning

Such improvements were already having an impact by 1998, when our third Great Lakes gale came on the scene. On November 9, the GOES satellite picked up a deepening storm system in southeast Colorado. Like its infamous predecessors, this extratropical cyclone explosively strengthened and headed toward Lake Superior.

Guided by the jet stream, the system tracked east and then curved northeast, rapidly intensifying as it moved. At 10 A.M. EST November 9, the NWS issued Lake Superior gale warnings for that evening. At 4 P.M., forecasters issued storm warnings for November 10, with waves expected to be 12 to 20 feet (3.7 to 6.1m) by that evening. But as the storm's center



THE MONSTER STORM that doomed the *Edmund Fitzgerald* bears down on the Great Lakes November 9, 1975. The "L" marks the storm's lowest pressure; red and blue arcs show the storm's cold and warm fronts, respectively. The storm's comma-shaped cloud pattern is characteristic of mature extratropical cyclones. At the time of this image, the storm was racing northeast toward the Great Lakes at 40 mph (64 km/h). DMSP

THE FIRST COLOR IMAGE of Earth from space, returned November 18, 1967, from NASA's ATS-3 spacecraft, illustrates the beauty and complexity of our planet's active atmosphere. NASA

arrived in northwest Iowa on the morning of November 10, the NWS forecast required no major changes.

GOES satellites allowed forecasters to analyze animations of clouds and moisture content throughout the storm. Forecasters could overlay the satellite images with other weather observations to track the storm more precisely. GOES images clearly showed the storm's rapid movement and developing organization.

On November 11, the mature storm's surface winds averaged between 50 and 60 mph (80 to 97 km/h) — with gusts to 93 mph (150 km/h) at La Crosse, Wisconsin. The strong sustained winds created an 11-foot (3.4m) difference in Lake Erie water levels between Toledo, Ohio, and Buffalo, New York.

Despite the 1998 storm's equal intensity to its predecessors, no lives were lost in that November gale. The memory of the *Edmund Fitzgerald* is partly responsible for this success — ship captains dropped anchor in sheltered areas rather than risk open water. Better weather observations and faster dissemination of weather information helped improve the accuracy of warnings.

Today, more than 120 U.S. space-based instruments observe our planet.

Bright future

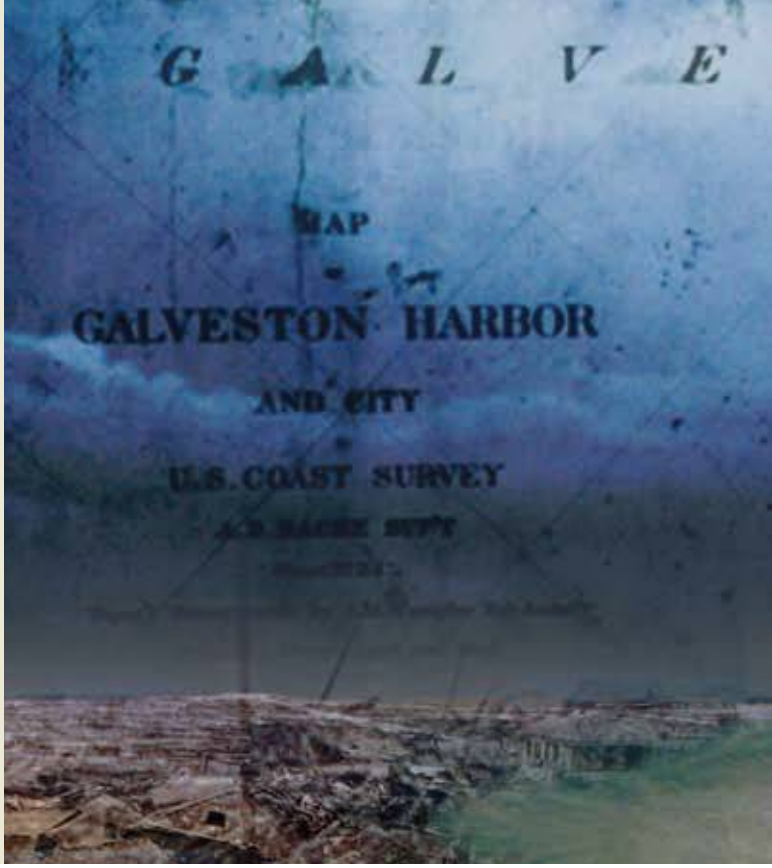
Today, more than 120 U.S. space-based instruments observe our planet. Future systems currently in development will help improve our ability to monitor and forecast storms.

The Advanced Baseline Imager (ABI), the next-generation camera for new GOES satellites, is slated for launch around 2014. The ABI will probe 16 spectral bands, provide double the spatial resolution now available, and image at least 3 times faster than current GOES systems.

The additional spectral channels will enable development of new products, such as reports indicating the presence of supercooled clouds that pose a risk to aircraft. The increased spatial resolution will allow forecasters to better monitor small-scale storm features. And faster scanning improves storm tracking and enables meteorologists to keep a watchful weather eye over a greater area. In addition, the next decade's GOES satellites will carry a lightning mapper designed to pinpoint the location and frequency of lightning bolts. This will enable forecasters to better warn the public of approaching severe thunderstorms.

Other nations have just as much interest in observing weather from space as the U.S. does. And international collaborations organized through the World Meteorological Organization offer a powerful way to understand weather on a global scale. In fact, an ambitious project called the Global Precipitation Mission aims to use a constellation of international satellites to map global precipitation patterns every 3 hours beginning about 2015.

We have much to learn about the vagaries of weather. One of the most important means of doing so involves a growing fleet of spacecraft dedicated to the task of watching our skies.



Low-lying land, dense development, and little warning set up Texas' island city for the worst weather disaster in U.S. history.

By Daniel Pendick

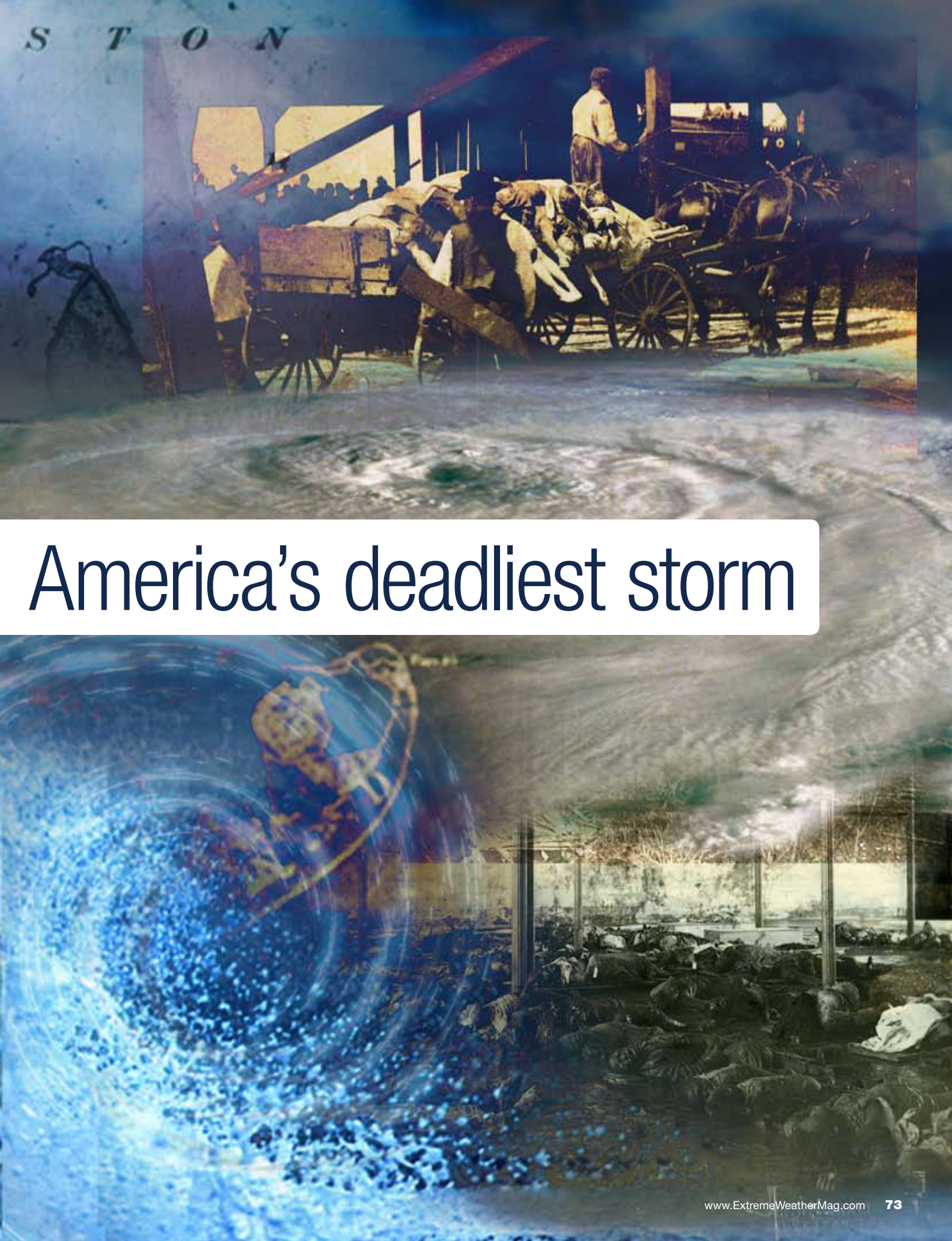
How Galveston **survived**

By 1900, the citizens of Galveston, Texas, had achieved unprecedented economic prosperity. The city, built on a shallow, sandy island 2 miles (1.2 kilometers) offshore, had become the state's leading center of trade, exporting some 1.7 million bales of cotton annually. At the turn of the century, the city stood in the doorway to an even more prosperous future.

This all changed September 8, 1900, when an unusually high tide and long, rolling sea swells gave way to a massive landfalling hurricane. During the night, the storm destroyed some 3,600 buildings and killed at least 6,000 residents out of a total population of about 38,000. Some estimates put the death toll as high as 10,000. The storm remains the most deadly natural disaster in U.S. history.

Even after a century of retelling, the tale of the great Galveston hurricane still chills us with the scale of its devastation and the sudden, anonymous loss of life. Today, 10 miles (16 km) of massive concrete seawall stands between the city of

EXTREME WEATHER: KELLIE JAEGER



America's deadliest storm

GALVESTON'S FISHING FLEET contributed much to the city's prosperity in the decades before the great storm. Oystermen harvested Galveston Bay's shellfish beds and returned with their boats heaped full. NOAA

Galveston and the sea, reminding all behind it of the fantastically destructive potential of tropical storms.

A wave of profits

Galveston, presently home to about 57,000 people, sprawls across a barrier island. It is connected to the coast by a causeway at the island's north shore, a bridge on the western side, and a ferry terminal on the east end. The island, 27 miles (43 km) long, varies in width from 1.5 to 3 miles (2.4 to 4.8 km). Salt marshes fringe its north shore. On the south coast, miles of hard-packed, caramel-colored sand afford an unrivaled recreational beachfront.

Established in 1838, the town had the best natural harbor on the Texas coast. This good fortune, and later improvements to the harbor, eventually allowed even the largest ocean-going freighters to add Galveston to their ports of call.

The city developed into an important center of export. And not just from Texas and surrounding states: By century's end, Galveston was less than 2 days by steam locomotive from Chicago and its hyperactive commodities markets.

On the eve of the great storm, Galveston was one of the country's major shipping ports. Cash from the sale of King Cotton poured in. Hotels rose. The newly wealthy built castle-like mansions in town. The saloons were packed, and the streets were bustling with activity.

In the 1870s and 1880s, Galveston became the most populous city in Texas, with 22,000 year-round inhabitants. In the summer season, even more people swarmed the beaches, bathhouses, and elegant hotels. Then came the storm.

Stormy water

Galveston had withstood at least 11 hurricanes before the 1900 storm. The historical record on these storms is either telegraphic in its lack of detail or virtually absent. But it's clear the major hazard had been, and remains, high storm tides.

As a tropical storm approaches the coast, strong surface winds and low central pressure mound up water in front of the tempest. This storm surge adds to the daily high tide, creating abnormally high water and coastal flooding. Storm tides 3, 6, 9, or even 12 feet above normal are not unheard of during a major storm.

Storm tides destroy coastal development and threaten the lives of anyone caught unaware. But in a setting like Galveston — dense development on a low-lying island — the potential for devastation and loss of life is much worse. A large storm tide can wash over the entire island as the tempest makes landfall.

During the 1900 storm, a tsunami-like wall of water bulldozed everything in front of it. As the wall of debris gained mass, its destructive power also grew. The storm tide also flowed around to the bay side of the island and flooded the city from the north. There was no escape from the vise-like meeting of the waters.

Isaac Cline

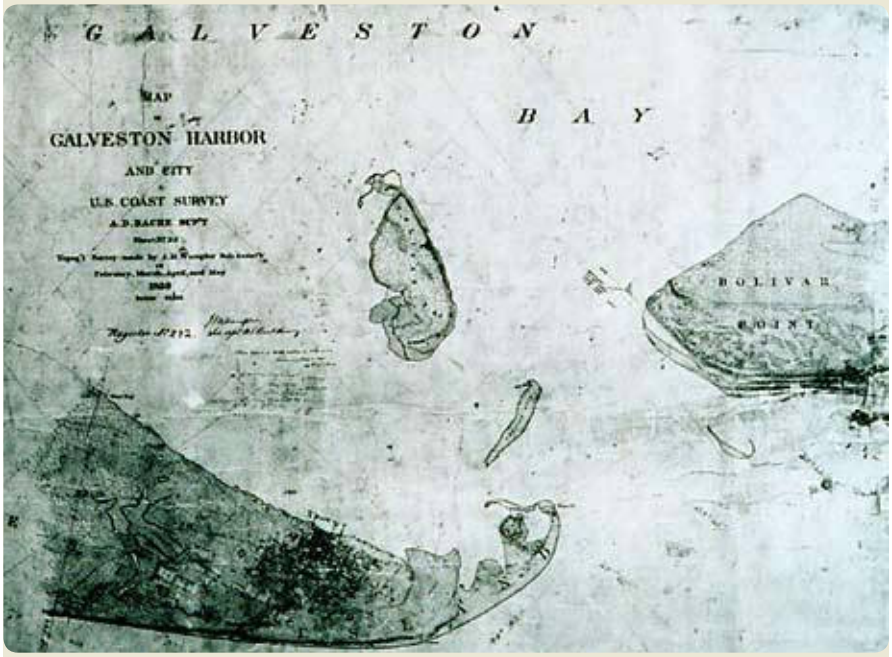
The only possible escape from such a storm would have been to get out of town in time to miss it. Unfortunately, weather forecasting in 1900 was primitive compared to today's capabilities. But Galveston did have a resident weather expert: Isaac Monroe Cline.

Cline (1861–1955) was born in Tennessee. He was an excellent student, and considered becoming a preacher or a lawyer. Instead, in 1882 he joined the U.S. Army Signal Corps, the predecessor to today's National Weather Service.

In 1889, Cline moved from Abilene, Texas, to Galveston with his wife, Cora, and their three daughters. Cline went there to start a new weather station and run the Weather Service's Texas branch. In 1891, Congress transformed the Weather Service into a new civilian agency, the U.S. Weather Bureau.

ISAAC CLINE, a meteorologist with the U.S. Weather Bureau in Galveston, did not see the great hurricane of 1900 coming in time for people to flee the doomed city. NOAA

GALVESTON ISLAND is a detached barrier beach southeast of Houston. Improvements started in the 19th century to insure a wave-protected, deep harbor for even the largest ocean-going vessels. *EXTREME WEATHER:* THEO COBB

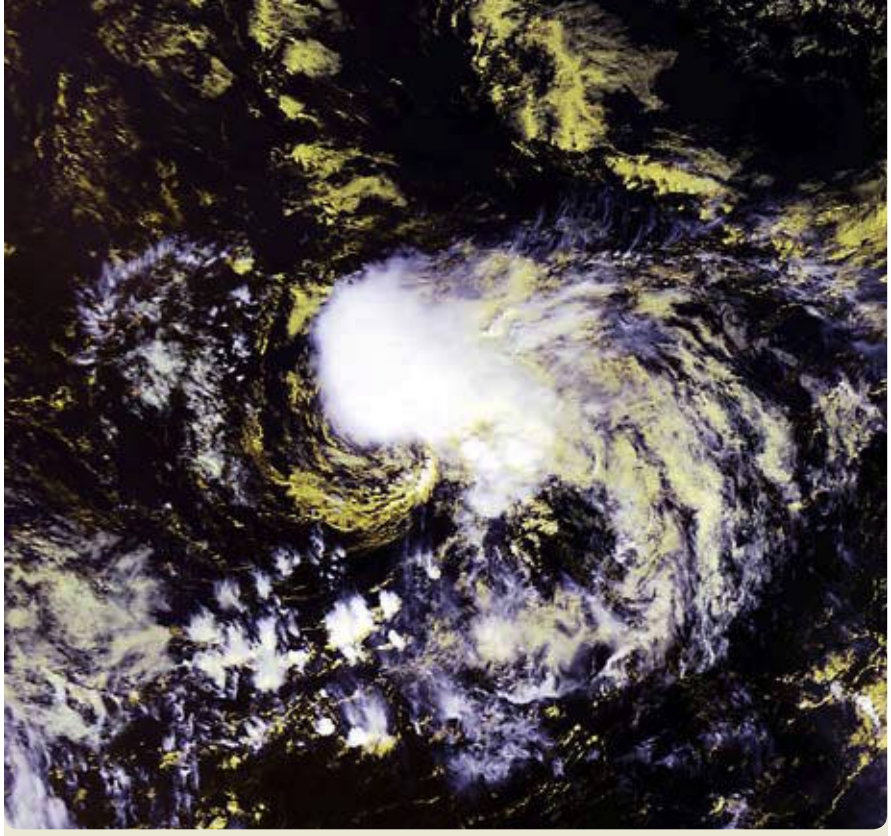


BY 1850, when surveyors completed this map of Galveston Island's east end and harbor area, the city was a major center of trade. Cotton exports fueled the city's rapid growth. NOAA

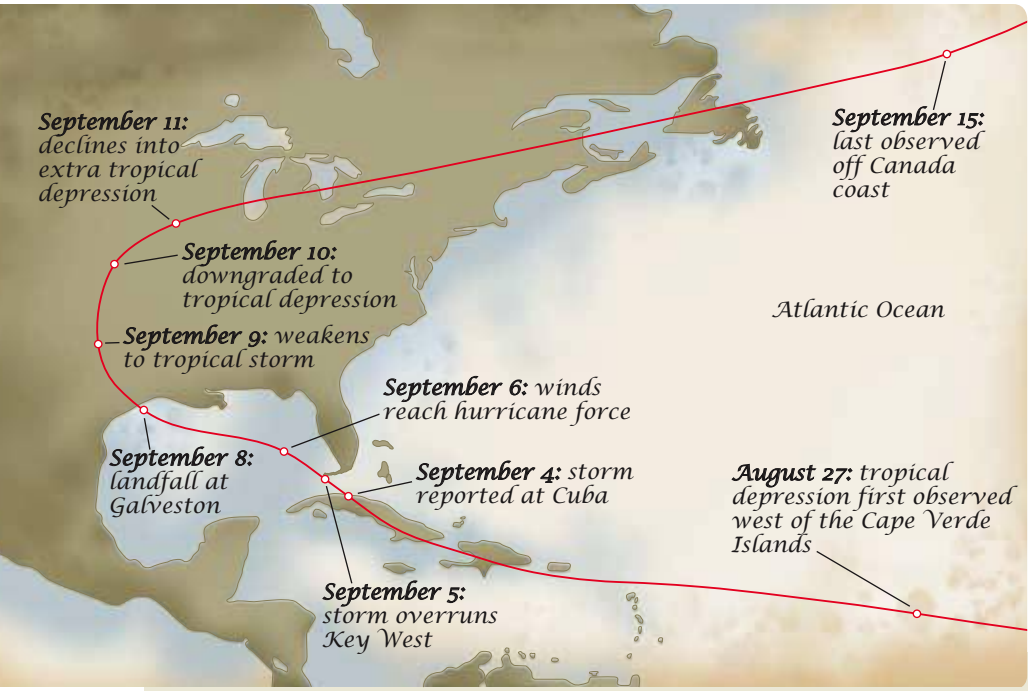
The young meteorologist had already begun to make a reputation for himself. He issued the first 24- and 36-hour temperature forecasts and freeze alerts to help farmers. He also fostered cooperation with weather forecasters in Mexico. But Cline did not have the tools or knowledge to anticipate the great storm.

By August 27, the storm had it organized to form a tropical depression — a system of thunderstorms with a low-pressure center and internal winds — west of the Cape Verde Islands. The next day, a ship's captain recorded steady winds of Beaufort Force 6 (25–31 mph [40–50 km/h]). The weather system continued to grow in intensity as it barreled across the warm Caribbean Sea.

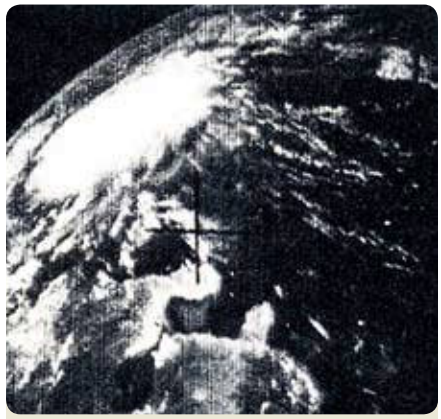
The Weather Bureau knew of the storm's existence as early as August 30.



SATELLITES TRACK HURRICANES from birth. In this image captured by the NOAA-18 weather satellite, Tropical Depression 15 — a cluster of thunderstorms with the potential to become a hurricane — hovers southeast of Bermuda. The depression ultimately weakened and died, as do most hurricane "seeds." NOAA


September 11: declines into extra tropical depression
September 10: downgraded to tropical depression
September 9: weakens to tropical storm
September 8: landfall at Galveston
September 6: winds reach hurricane force
September 4: storm reported at Cuba
September 5: storm overruns Key West
August 27: tropical depression first observed west of the Cape Verde Islands
September 15: last observed off Canada coast
Atlantic Ocean

THE GREAT GALVESTON HURRICANE, first sighted as a tropical disturbance off Africa's west coast by a ship captain, rolled across the Caribbean Islands and Cuba before reaching the Gulf of Mexico. Forecasters expected it to turn north, but it headed west instead. The cyclone intensified into a major storm before making landfall near Galveston September 8, 1900. The storm, weakened but alive, churned across the entire continent, causing death and destruction. It finally died offshore. *EXTREME WEATHER:* THEO COBB



THE TIROS III weather satellite provided the first global hurricane tracking. In this 1964 image, the satellite monitored its first cyclone, Hurricane Anna. Until then, nobody could truly see a hurricane coming. NOAA

The Bureau also knew that the storm passed over Cuba September 4, heading north. On September 6, it churned northwest of Florida's Key West.

Expecting the storm to recurve eastward, as most Atlantic tropical storms did, Weather Bureau forecasters in Washington issued warnings to the eastern Gulf Coast, Florida, and southern states on the Atlantic. Instead, the storm turned west into the warm waters of the Gulf.

On September 7, the day before landfall, Cline noticed an upturn in the size and frequency of swells reaching Galveston. The long, rolling waves were the leading edge of the storm surge.

Cline also noticed that the tide was rising. This made no sense, because the wind was blowing from the north, not from the south, which might have explained the higher tide. Nor had the barometer started to fall — another sign of a tropical storm.

Cline eventually decided a storm was coming from the sea. He ordered warning flags flown in town. According to his later memoir, Cline drove a horse and wagon along the beach at 5 A.M. the morning of the storm, to warn people to seek shelter on higher ground.

But little high ground existed in Galveston. The highest point stood only 8.7 feet (2.7m) above sea level. A storm tide estimated at 15 to 20 feet (4.6 to 6m) was coming, but most people remained in their homes. The Weather Bureau never even used the term "hurricane." The lack of safe refuge and adequate warning doomed the city's inhabitants.

THE GALVESTON HURRICANE bulldozed portions of the city up to 15 blocks from the beach. Some 3,600 structures were smashed into chaotic mix of splintered wood, broken glass, smashed furniture, and dead bodies. COURTESY OF THE ROSENBERG LIBRARY, GALVESTON, TEXAS

Why didn't Cline and the Weather Bureau see the disaster coming? Cline's own bias probably played a role. In 1891, he published an article in a Galveston newspaper dismissing the "absurd delusion" that Galveston was at risk from hurricanes. He stated that, because of Earth's rotation and large-scale wind patterns, tropical storms turn eastward before reaching the Gulf, except under very unusual circumstances. And even if a cyclone made it to the Texas coast, Cline argued, it would be relatively weak.

As for flooding, Cline believed storm tides would preferentially inundate the low-lying mainland coast, not Galveston. "It would be impossible," he wrote, "for any cyclone to create a storm wave which could materially injure the city."

Disaster day

Cline's expectations proved tragically inaccurate. The storm enveloped Galveston the evening of September 8 with winds gusting as high as 140 mph (225 km/h). Cline and his brother Joseph, who also worked at the Weather Bureau, reported observations to Washington until the telegraph lines went down.

Like so many others, they returned home to wait out the tempest. Cline's family and about 50 neighbors huddled in the house. During the storm, a railroad trestle broke free and struck the Cline home, tearing it apart. Isaac, his brother, and his daughters made it out of the wreckage of the house alive, but Cline's wife drowned.

By 6 P.M. Saturday, the wind tore off the gauges at 100 mph. A dark, deadly night was coming. At about this time, Samuel O. Young, secretary of the city's

AUTHORITIES AT FIRST COLLECTED CORPSES for burial at sea. But the bodies floated back and washed up on shore. COURTESY OF THE ROSENBERG LIBRARY, GALVESTON, TEXAS

HUMAN REMAINS from the city's wreckage awaited cremation in makeshift morgues like this one. The burning continued for more than 6 weeks. COURTESY OF THE ROSENBERG LIBRARY, GALVESTON, TEXAS

GALVESTON'S NEW COASTAL DEFENSE SYSTEM included a massive wall that stood between the sea and most of the city center by 1904. Subsequent additions extended the wall for 10 miles (16 kilometers). COURTESY OF THE ROSENBERG LIBRARY, GALVESTON, TEXAS

TO GUARD AGAINST FLOODING, Galveston residents jacked up their homes and businesses and piped in dredged sand to fill the space. When the sand drained, much of the city lay above flood-tide elevation for major storms. COURTESY OF THE ROSENBERG LIBRARY, GALVESTON, TEXAS

Cotton Exchange and Board of Trade, watched the mounting violence from his home. He had earlier observed the ocean start to encroach on the Strand, the city's opulent main drag.

Now, through a west window in his home, Young saw the tide rise full 4 feet in one pulse. Then he saw several large houses fall apart like toys and float away. Cline witnessed something similar: water rising from a depth of 8 inches to 4 feet on his first floor in the time it took for him to cross the room.

Texas historians have collected scores of equally harrowing personal accounts of the storm. A typical scenario of death saw people wading chest-deep in water and then climbing to the upper floors of buildings as the floodwater rose rapidly. Finally, the buildings collapsed, carrying many victims into the chaotic pile of splintered planks, broken glass, smashed furniture, and drowned bodies. And all this occurred in pitch darkness as the storm howled like a freight train. Venturing outdoors was certain death.

Galveston mourns

Charles Law, a traveling salesman who stayed the night in the Tremont Hotel, ventured outside Sunday morning after a night when he and many others waited helplessly for death. "I went out into the streets and the most horrible sights you can ever imagine," he later recounted in a letter to his wife. "I gazed upon dead bodies laying here and there. The houses all blown to pieces. . . And when I got to the gulf and bay coast, I saw hundreds of houses all destroyed with dead bodies all lying in the ruins, little babies in their mothers' arms."

The authorities first tried to dispose of the bodies by towing them in barges out to sea. But the bloated corpses floated back to shore. Most bodies were burned in large pyres onshore, a process that continued for more than 6 weeks. Family, friends, and neighbors watched as about 1 in every 6 of their number went up in smoke with the wreckage of the city.

The storm headed inland as far as Ontario, Canada, weakened but still dangerous. Thirteen lost their lives on Lake Erie with the sinking of two steamships. The Canadian fishing fleet took heavy losses of ships and sailors. The storm headed into the North Atlantic September 13 and eventually died.

City on the mend

The great storm had proved Isaac Cline tragically wrong about Galveston's vulnerability to hurricanes. In response, the survivors decided to harden Galveston Island against flood tides and surf. On the ocean coast, Galveston built a massive seawall to protect the city's core. It has grown over the years. Today, the concrete wall measures 16 feet (4.9m) at its base, rises 15.6 (4.8m) feet above sea level, and spans more than 10 miles (16 km).

To protect against flooding, engineers raised the island's elevation, pitching it 1 foot per 1,500 feet of distance from the high side at the seawall toward the north shore. This required 16 million cubic yards of fill. Buildings were raised on

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WAVES CHURNED UP by tropical storm Fay pounded homes on Galveston's densely settled coast in 2002. ASSOCIATED PRESS

A SEAWALL STANDS GUARD on Galveston's southern coast against hurricane-driven flooding and waves. But even with its high level of preparedness, the city could take another punishing blow from the sea, less deadly but far more costly than the 1900 disaster. ASSOCIATED PRESS

screw jacks so sandy fill could be pumped underneath. The same went for sewer and gas lines.

The fill material was a slurry of water and sand dredged from the ship channel between Galveston and Pelican Island. Workers pumped it through pipes into the spaces beneath the suspended buildings. Gradually, the fill drained and hardened. By 1911, some parts of the city were raised as much as 11 feet (3.4m).

Life went on for Cline, too. He moved to New Orleans in 1901 to become forecaster-in-charge of the Weather Bureau's Gulf District. He was responsible for the coast stretching from Texas to Florida.

In addition to his regular duties, Cline continued to study tropical cyclones. He developed a method for tracking and forecasting storm trajectories based on detailed meteorological data collected in front of and to the sides of storms. Cline collected detailed data on 16 cyclones from 1900 to 1924. He published his observations and methods for charting storms in a book, *Tropical Cyclones*, in 1924. Cline retired in 1935. He remained an art dealer in New Orleans' French Quarter until his death in 1955.

Storms to come?

The reconstruction of the Oleander City buried most of Galveston's trees and well-maintained gardens and greenery. So were the graves of many past residents. Galveston was, in a real sense, a city whose slate had been wiped clean and rewritten.

One fact about Galveston remains the same: It is vulnerable to attack from the sea. After a 1915 hurricane comparable to the 1900 tempest, much of the city flooded, although not catastrophically. Structures behind the seawall generally survived the onslaught.

But as the 2005 Hurricane Katrina disaster reminded us, it never pays to underestimate the destructive potential of hurricanes. Although we may be able to forecast storms much better and mandate evacuation plans that can save thousands of lives, nothing can stop a hurricane on the move — except its collision with the coast. Galveston and thousands of other seaside communities can only wait to see what nature has to dish out in future storms.

Top 12 weather myths

Every science has its folklore and untruths. Here's meteorology's dirty dozen. **By Michael E. Bakich**

Some sayings about the weather are fun and harmless. For example, "A pot of gold waits at the end of the rainbow" isn't true, but so what? Nothing bad can come of it. Believing other weather myths, however, may lead you to the wrong decisions when your life is at stake. Here's the truth about a dozen of the most prevalent weather myths.

1 Lightning never strikes the same place twice.

In fact, lightning repeatedly strikes the same objects. Some office buildings get hit many times a year, as do mountains and broadcast antennae. Lightning strikes the Empire State Building an average of 23 times a year.

Cloud-to-ground lightning hits the same place because the electrical charge potential gets strong enough to overcome the electrical resistance of air between a cloud base and objects — usually high ones — on the ground. If lightning strikes a tall object once, it probably will again.

2 Because of Earth's rotation, water flows down drains in opposite directions in the Northern and Southern Hemispheres.

People repeating this myth cite the Coriolis effect, produced by Earth's rotation, as the cause. The Coriolis effect is an apparent force that is zero at the equator. North of the equator, the deflection of an object (like wind) is to the right. In the Southern Hemisphere, the deflection is to the left. The deflection's strength depends on how far you are from the equator.

Although the Coriolis effect influences wind flow over large distances, it has no effect over short distances, such as in a sink. The direction water drains from toilets, sinks, and bathtubs depends on the unit's construction.

3 Heat generates lightning.

Many people call faint flashes of lightning on the horizon or in clouds from distant storms "heat lightning." Such lightning discharges have no accompanying sounds of thunder, and usually they lack a classic "bolt." Heat lightning probably got its name because it often occurs on hot summer nights.

Two possible reasons account for the lack of thunder. In some cases, the storm may be too far to enable hearing thunder from the lightning discharge. Thunder rarely travels more than 10 miles (16 km). Heat lightning, therefore, can warn that thunderstorms are approaching.

Another reason you may not hear thunder is because air layers with different densities refract (bend) the sound. An observer may see lightning, but air layers divert the thunder's sound.

So, next time you hear the word "heat" associated with lightning, substitute the word "distant."

4 Groundhog Day determines the length of winter.

Because of the national attention this myth gets annually, it may be the one most hated by meteorologists. Simply put, if the groundhog Punxsutawney Phil (who resides in a wooded knoll near Punxsutawney, Pennsylvania) sees his shadow February 2 — now known as Groundhog Day in the United States — winter will last 6 more weeks. This legend comes from the Scottish saying, "If Candlemas Day (February 2) is bright and clear, there'll be two winters in the year."

Groundhog Day proponents say the rodent's forecasts are accurate 90 percent of the time. A study in *The Canadian Encyclopedia* for 13 cities in the past 40 years puts the success rate at 37 percent. Also, the National Climatic Data Center in Asheville, North Carolina, reported the overall prediction's accuracy rate since 1887 is 39 percent. Random chance (like a coin flip) would give a rate of 50 percent.

5 Rubber tires on your automobile (or rubber-soled shoes) insulate you from lightning strikes.

Automobile tires offer no protection from lightning strikes — but the car's steel body can shield occupants. Lightning (in fact, all electricity) will take the path of least resistance between two points. When it strikes a car, the least-resistive path to the ground is along the outside metal skin, not through it.

If you're in a hardtop vehicle, you are protected from the dangers of lightning. Unfortunately, a convertible offers no such protection.

A related myth says rubber-soled shoes offer lightning protection. Don't believe it. Such shoes are ineffective in insulating you from lightning dangers.

6 A person struck by lightning retains an electrical charge and should not be touched.

The human body does not store electrical energy. Qualified individuals can administer first aid to a victim immediately after a lightning strike. The victim will not retain any electrical charge.

Be certain that lightning struck the victim, and that the storm didn't down a power line, which caused the shock. If a wire still contacts a victim, do not touch the person, or you may be electrocuted.

7 The best place to be during a tornado is in the southwest corner of a building or basement.

Tornados generally approach from the southwest, so some people advise moving

toward where the tornado will strike. The thinking here is that debris will be blown to other parts of the building. Actually, the safest place is an interior room on the north side of the building or basement.

The part of the building toward the approaching tornado is always the worst location to shelter. Research has shown that the northeast corner is twice as safe as the southwest corner. The safest location is underground, but, lacking that, the next best place is an interior room on a building's north side away from outside walls and glass.

Abandon trailers and mobile homes, and move to an approved shelter. If no shelter is nearby, lie flat in a ditch with your hands shielding your head.

8 Opening windows to equalize air pressure will save a roof, or even a home, from destruction by a tornado.

Homes are damaged by strong winds, not air-pressure changes during tornados. Even with all windows closed, most houses and commercial buildings have enough openings to vent the pressure difference in the time it takes for a tornado to pass. Texas Tech's Institute for Disaster Research team reports the pressure drop inside the strongest tornado — an F5, with 260 mph (419 km/h) winds — is only about 10 percent.

Buildings can equalize this small pressure drop in a few seconds. Structural vents will deal with this inequality even if the tornado approaches rapidly. So, the buildup of air pressure inside the structure will not destroy it, but a tornado's violent winds could.

Follow the National Weather Service's advice: "Leave the windows alone, the tornado will open them for you."

9 You can outrun a tornado in your vehicle.

The automobile is one of the worst places to be during a tornado. If all factors are in your favor, you may be able to outrun a tornado. All factors, however, seldom favor someone trying to outdrive a tornado.

First, from a car, it's hard to tell which way the tornado is going. Second, nothing says it will continue to move in the same direction. Third, the tornado you see may not be the only one — a second could form near you. Fourth, you still need to obey traffic signals and signs. Other drivers may not know a tornado is in the area. You're putting them at risk if you disobey traffic laws. Also, you need to follow the road; the tornado doesn't.

If other drivers know of the danger and are simultaneously trying to escape, you'll find yourself in a giant traffic jam. One of the deadliest examples of trying to outrun a tornado occurred in Wichita Falls, Texas, April 10, 1979. The tornado killed 16 people trying to drive out of the twister's path when they became stuck in traffic. Eleven of those 16 left homes that were undamaged.

A car is a poor place to be because a tornado's winds can blow vehicles around. Many tornado fatalities occur because drivers refuse to leave their vehicles.

During the 1994 DeSoto, Texas, tornado, a driver was seriously injured when the vehicle she was driving was thrown into the second floor of a building. If you're in a motor vehicle and a tornado is near, abandon the vehicle and take cover in a ditch or ravine.

10 You can use your television set (or AM radio) as a tornado detector.

This method of tornado detection was popular in the 1960s and early 1970s. In some cases, it was possible to detect tornados using a TV or AM radio. The technique depends on severe thunderstorms that contain a tornado also containing large amounts of lightning. The TV technique involved turning the television to Channel 13, turning down the brightness till the screen was almost black, then switching to Channel 2.

As a tornado developed, lightning would cause the screen to turn bright white. This happened because Channel 2 lies near the same frequency as the signal produced by the lightning and would override the brightness control.

On an AM radio, the static would become continuous at 550 kilohertz, at the low end on the dial. This method sometimes works, but it's not foolproof.

The main reason is that tornados can form when the parent cloud contains little lightning. Your TV also can signal "tornado" when it's really showing a non-tornadic thunderstorm containing a large amount of lightning.

Some television sets now employ filters to prevent this effect from happening. Also, millions of people now receive TV signals through a cable provider. If you are one of them, this technique will not work. But even with "old-fashioned" televisions, this method produced too many false alarms and missed many tornados that did form.

11 Highway overpasses can provide safe shelter if you are on the road when you see a tornado coming.

This myth is one of the most dangerous because many people have seen one or more film clips showing people — most notably a television news crew filming a tornado — seeking shelter under an overpass and surviving.

Since those clips aired — and because the news crew survived — many people assume highway overpasses provide safe shelter. The opposite is true: An overpass does not protect you from a tornado's winds. Anytime you put yourself above ground level during a tornado, you are in harm's way. Drivers who pull over on the highway and run up under highway overpasses not only risk injury or death, but also they put other motorists in jeopardy by blocking the road near the overpass.

12 Tornados never strike big cities.

Many people believe living in a large city protects them from tornados. This is not true. The odds may be lower because of the small areas covered, but a tornado's path can go anywhere.

The list of major cities struck by tornados includes Atlanta (2008); Charleston, South Carolina (1938); Dallas (1894); Des Moines, Iowa (2007); Detroit (1997); Fort Worth, Texas (2000); Greensboro, North Carolina (1936); Houston (1993); Huntsville, Alabama (1989); Indianapolis (1927); Jacksonville, Florida (2004); Kansas City (1883); Little Rock, Arkansas (1999); Los Angeles (2004); Louisville, Kentucky (1890); Lubbock, Texas (1970); Miami (1997); Nashville (1933, 1998); New Orleans (2006, 2007); New York City (1974, 1985, 1990, 1995, 2003, 2007); Omaha, Nebraska (1913); Philadelphia (1999); Richmond, Virginia (1951); Salt Lake City (1999); San Antonio, Texas (1994); St. Louis (1871, 1890, 1896, 1927, 1959, 2007); Waco, Texas (1953); and Washington (1888).

Weather products

WeatherNow II with MSN Direct Service

Oregon Scientific, Tualatin, Oregon

This weather station uses MSN Direct service to receive regional weather information without outdoor sensors. Users get real-time, 4-day weather forecast information and current regional weather data, including temperature, humidity, UV index, and a "feels like" temperature reading that combines temperature and humidity into one number. A radio-controlled clock/calendar displays the day's sunrise and sunset information. The unit operates on a 6-volt AC adapter (included) and uses 4 AA batteries for backup (included).

Price: $129.95; [t] 800.853.8883; [w] www.oregonscientific.com

Weather Forecaster with Temperature and Humidity

Oregon Scientific, Tualatin, Oregon

This unit uses barometric pressure to predict weather 12 to 24 hours in advance. The backlit display features temperature and humidity readings from up to three locations (one sensor included). A digital clock sets itself to the U.S. Atomic Clock radio signal, and the calendar has a Moon-phase indicator. The main unit measures 2.6" by 2.75" by 6.1" (6.6cm by 7cm by 16.8cm).

Price: $59.95
[t] 800.853.8883
[w] www.oregonscientific.com

Emergency Public Alert Radio

Oregon Scientific, Tualatin, Oregon

The Emergency Public Alert Radio informs you of civil and weather disasters. The portable unit has rechargeable batteries, a charging dock, and a belt clip. This radio monitors U.S. Emergency All Hazards and Emergency Alert System weather bulletins and warnings. It receives all National Oceanic and Atmospheric Administration reports, which provide emergency advisories on tornados, floods, and evacuations.

Price: $89.95
[t] 800.853.8883
[w] www.oregonscientific.com

Advanced Weather Station with Wireless Sensor Set

Oregon Scientific
Tualatin, Oregon

This station monitors six different weather measurements. The unit includes five sensors for weather information, and you can add nine temperature-humidity sensors. Wireless sensors transmit data from up to 300 feet (91m) from the main unit. The instrument displays temperature, humidity, barometric pressure, wind, rainfall, dew point, wind-chill, and heat-index data. A wind sensor provides information on speeds, gusts, and directions. The station adjusts for Daylight Saving Time and displays a Moon-phase icon.

Price: $179.95
[t] 800.853.8883
[w] www.oregonscientific.com

Complete Wireless Weather Station

Oregon Scientific, Tualatin, Oregon

This weather station comes equipped with solar-powered outdoor sensors. Long-range sensors transmit up to 300 feet (91 meters) from the main unit. A large, illuminated LCD touch screen lets you work in the dark.

The station includes four sensors: an anemometer; a self-emptying rain gauge; a sensor that measures indoor temperature, humidity, and barometric pressure; and a sensor for outdoor temperature and humidity. This station has seven channels and accepts up to three additional sensors. The unit is PC-compatible (with optional cable and software). The kit contains an AC adapter and batteries for the base unit and the indoor sensor. Solar-powered, remote sensors use two AA batteries for backup (not included). The station measures 8.5" by 1.75" by 5.5" (21.6cm by 4.4cm by 14cm).

Price: $299.95
[t] 800.853.8883
[w] www.oregonscientific.com

SkyScan Lightning/Storm Detector

Xtreme Research Corp.
Port Richey, Florida

The portable, handheld SkyScan Lightning/Storm Detector detects electromagnetic emissions from lightning strikes and thunderstorm activity within 40 miles (64 kilometers) of its location. A warning tone sounds when it detects a lightning strike.

Price: $239.95
[t] 888.732.0665
[w] www.xgun.com

Stormy-day reading

Check out these seven books for more information about extreme weather. **By Michael E. Bakich**

Mark Levine • Miramax Books, 2007 • $25.95

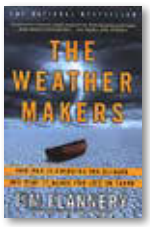
F5: Devastation, Survival, and the Most Violent Tornado Outbreak of the Twentieth Century

On April 3, 1974, a megastorm rampaged through the central United States, unleashing at least 148 tornados. Six of them attained the rare and overpowering F5 category, with sustained winds above 260 mph. The storm killed hundreds of people and caused billions of dollars in property damage.

Author Mark Levine focuses on the impact in rural Limestone County, Alabama, where dozens of tornados cut ruinous swaths across the land. Levine puts the reader in the minds of Limestone's residents — a high school freshman, the local sheriff, a power lineman — whose lives the storm upended.

Tim Flannery • Atlantic Monthly Press, 2006 • $15

The Weather Makers: How Man Is Changing the Climate and What It Means for Life on Earth

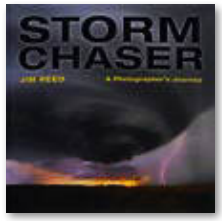


The Weather Makers presents a straightforward and powerfully written look at the connection between climate change and global warming. Tim Flannery focuses on the natural forces that produce devastating events. He offers succinct and fascinating insights into topics such as the greenhouse effect, global warming, climate change, and El Niño, and covers the profound reorganizing effect each has had on nature.

The heart of the book deals with Earth's carbon-dioxide pollution problem. Flannery suggests we shift from our current global reliance on fossil fuels, which makes us all "weather makers" who already possess all the tools required to avoid catastrophic climate change, to more environmentally friendly alternatives.

Jim Reed • Harry N. Abrams, 2007 • $35

Storm Chaser: A Photographer's Journey

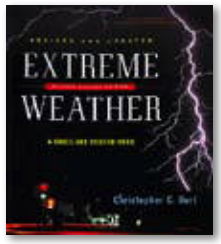


On-air weather forecasters report local and national meteorological conditions after the televised news. For storm chaser Jim Reed, it is the news. Tracking news-making weather, Reed has compiled dramatic images of tornados, lightning storms, and other extreme and unusual weather phenomena.

Reed, for 15 years one of America's most successful storm chasers, has documented a change. As the years go by, he's seen hotter summers, and an increase in the number and intensity of tornados and hurricanes. In *Storm Chaser: A Photographer's Journey*, a beautiful picture book about some of the most powerful and deadly phenomena, Reed shares his best images and experiences as he tracks storms throughout the country.

Christopher C. Burt • W. W. Norton, 2007 • $25.95

Extreme Weather: A Guide and Record Book



Extreme Weather tackles the big questions: Is the climate becoming more extreme? Will the extraordinary hurricane season of 2005 and the record heat waves of 2006 become more common?

Christopher C. Burt gives a detailed analysis of extreme-weather trends in the United States back to the 19th century. He also includes historical examples of some of the more bizarre weather events meteorologists have observed: heat bursts, electrified dust storms, snow rollers, pink snowstorms, luminous tornados, falls of fish and toads, ball lightning, super bolts, and other strange meteorological events. *Extreme Weather* contains 110 color photographs.

Robert Henson • Rough Guides, 2006 • $16.99

The Rough Guide to Climate Change

The Rough Guide to Climate Change is a complete guide to one of humanity's most pressing problems. Robert Henson covers the current situation, background science, skeptical arguments, and possible solutions. Chapters highlight how global warming works and how our atmosphere has evolved during the past 4.5 billion years.

Henson addresses the role the media plays in conveying the facts about climate change. The guide also includes lifestyle advice and tips for consumers who want to make a difference in tomorrow's climate. It comes complete with a glossary of web sites for further information.

Robert Henson • Rough Guides, 2007 • $19.99

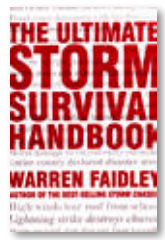
The Rough Guide to Weather

Whether you're an adventurer who enjoys wild weather, a traveler seeking climate details for Madagascar or Mumbai, or simply are curious about those maps on the evening news, *The Rough Guide to Weather* is what you need.

Henson explains world climate and weather science, and gives tips on how to read the sky and make sense of a forecast. Illustrated throughout with photographs, climate charts, and hundreds of Internet links for every continent, this guide will help you understand the weather.

Warren E. Faidley • Rutledge Hill Press, 2006 • $12.99

The Ultimate Storm Survival Handbook



Since 1980, weather-related disasters have caused more than 618,000 fatalities and cost more than $1.3 trillion.

The Ultimate Storm Survival Handbook explains what the warnings mean, and how to secure your home, take inventory of your belongings, create a plan for family survival, and more. Part Two of this book contains six storm survival checklists. Each of these tells you what to do in case you experience extreme weather.

GLOSSARY

Extreme weather **words**

Don't be confused by weather reports or forecasts. Here's what you need to know. **By Michael E. Bakich**

ADVISORY
A statement issued by the National Weather Service for probable weather situations of inconvenience that do not carry the danger of a warning, but which could lead to hazardous situations.

ANTICYCLONE
An area of high pressure with descending air movement. Anticyclones rotate clockwise in the Northern Hemisphere and counter-clockwise in the southern.

ASTRAPHOBIA
Fear of thunder and lightning.

ATMOSPHERIC PRESSURE
The weight exerted by the atmosphere at a given point, usually on the surface. Meteorologists express its magnitude in millibars, inches, or millimeters of mercury. Also known as barometric pressure.

BLIZZARD
A severe weather condition with winds 35 mph (56 km/h) or greater, and sufficient falling and/or blowing snow in the air to reduce visibility to ¼ mile (400 meters) or less for at least 3 hours. Low temperatures are common during blizzards. A severe blizzard (also called a whiteout) has temperatures below 10° F (–12° C), winds exceeding 45 mph (72 km/h), and zero visibility.

BOW ECHO
A radar echo signature often associated with severe thunderstorms, especially those that produce wind damage. It is bent outward in a bow shape.

BRONTOPHOBIA
Fear of thunderstorms.

CLOUD
A visible collection of water droplets and/or ice crystals that forms in the atmosphere due to water-vapor condensation. Condensation nuclei, such as in smoke or dust particles, form a surface upon which water vapor condenses.

CLOUDBURST
A sudden, heavy rainfall, sometimes mixed with hail and thunder, which usually lasts no more than a few minutes.

CUMULONIMBUS
A vertically developed cumulus cloud, often capped by a homogenous anvil-shaped cloud. Also called a thunderstorm cloud, it may produce heavy showers, lightning, thunder, hail, tornados, or strong, gusty winds.

CYCLONE
An area of closed pressure circulation with rotating and converging winds, the center of which is a relative pressure minimum. The circulation is counterclockwise in the Northern Hemisphere and clockwise in the southern.

DEPRESSION
An area of low pressure; a low, or trough.

DEW POINT
The temperature to which air must be cooled at a constant pressure for water vapor to condense into water (dew).

DOWNBURST
A severe localized downdraft from a thunderstorm or shower that produces an outward burst of cold air, which can create damaging surface winds.

DOWNDRAFT
A sudden descent of cold air to the ground, usually associated with a thunderstorm or shower.

DOWNPOUR
A heavy rain with a precipitation rate exceeding 0.16" (4 millimeters) per hour.

DROUGHT
Meteorological drought is a prolonged period of dry weather for a specific area. Agricultural drought is one which affects crop production. Hydrological drought occurs when water reserves (aquifers, lakes, etc.) fall below statistical averages.

DUST STORM
A severe weather condition characterized by winds strong enough to lift dust from a dry surface. Visibility is reduced to between 5/16 and 5/8 mile (0.5 and 1 km).

FLASH FLOOD
A flood that rises rapidly with little or no advance warning, usually as the result of intense rainfall over a relatively small area. Flash floods differ from regular floods because of their time scale, less than 6 hours.

FLOOD
High water flow or an overflow of rivers, streams, or other bodies from their natural or artificial banks, which inundates adjacent low-lying areas.

FREEZING RAIN
Rain that falls as liquid and freezes upon contact to form a glaze on the ground or other exposed surfaces.

FUJITA-PEARSON SCALE
A scale that classifies the severity of tornado wind damage based on the event's degree of destruction. Introduced in 1971 by Tetsuya Fujita of the University of Chicago. Two years later, Allen Pearson, head of the National Severe Storms Forecast Center in Kansas City added path length and width estimates. On February 1, 2007, the Enhanced Fujita scale went into effect. Meteorologists revised it to reflect more precise examinations of tornado damage surveys and to align wind speeds with tornado damage.

GALE
On the Beaufort Wind Scale, a wind with speeds from 28 to 55 knots (32 to 63 mph). In 1964, the World Meteorological Organization subdivided gale into near gale, 28 to 33 knots (32 to 38 mph), gale, 34 to 40 knots (39 to 46 mph), strong gale, 41 to 47 knots (47 to 54 mph), and storm, 48 to 55 knots (55 to 63 mph).

GUST
A sudden significant increase in or rapid fluctuation of wind speed. Peak wind must reach at least 16 knots (18 miles per hour) and variation between peaks and lulls is at least 10 knots (11.5 mph). Duration is usually less than 20 seconds.

HEAT INDEX
The combination of air temperature and humidity that gives a description of how the temperature feels to humans.

HEAT WAVE
A period of abnormally uncomfortable hot weather when the maximum temperature of more than 5 consecutive days exceeds the normal high temperature by 9° F (5° C).

HURRICANE
The name for a tropical cyclone with sustained winds of 74 miles per hour (65 knots) or greater in the North Atlantic Ocean, Caribbean Sea, Gulf of Mexico, and in the eastern Northeast Pacific Ocean. This same tropical cyclone is known as a typhoon in the western Pacific and as a cyclone in the Indian Ocean.

ICE STORM
A severe weather condition characterized by freezing rain. Such a storm forms a glaze on exposed surfaces, creating hazardous travel conditions and utility problems.

INVERSION
A departure from the usual increase of an atmospheric property with altitude. It usually refers to an increase in temperature with increasing altitude (temperature inversion),

which is a departure from the usual decrease of temperature with height.

LIGHTNING
A sudden, visible atmospheric discharge of electricity produced in response to the buildup of electrical potential between cloud and ground, between clouds, within a single cloud, or between a cloud and the surrounding air. Lightning typically occurs during thunderstorms, and sometimes may occur during volcanic eruptions, or dust storms.

LILAPSOPHOBIA
Fear of tornados or hurricanes.

MACROBURST
A large downburst with an outflow diameter of 2.5 miles (4 km) or larger, and damaging winds that spread outward.

MICROBURST
A severe localized column of sinking air blasting down from a thunderstorm. It covers an area less than 2.5 miles (4 km) in diameter and usually lasts less than 5 minutes.

MONSOON
The seasonal shift of winds created by the great annual temperature variation that occurs over large land areas in contrast with associated ocean surfaces. The monsoon is associated primarily with copious rains and is most evident on the southern and eastern sides of Asia. It also occurs in the southwestern United States.

RELATIVE HUMIDITY
A type of humidity (expressed as a percentage) that is the ratio of the actual vapor pressure of the air to the saturation vapor pressure.

SANDSTORM
A strong wind carrying sand particles through the air. Sandstorms usually measure only 10 to 50 feet (3 to 15 meters) above the surface. Because of winds created by surface heating, sandstorms are most predominant during the day and die out at night. Visibility is reduced to between 5/16 and 5/8 mile (0.5 and 1 km); if less than 5/16 mile, the storm is a heavy sandstorm.

STORM
An individual low-pressure disturbance, complete with winds, clouds, and precipitation, usually associated with severe, destructive, or unpleasant weather.

SUPERCELL
The largest class of thunderstorm, characterized by a rotating, intense updraft called a mesocyclone. Although uncommon, such storms can last for hours and produce large hail, damaging straight-line winds, and spawn practically all violent tornados.

THUNDER
The sound emitted by rapidly expanding gases along the channel of a lightning discharge. The "rumble" of thunder occurs as one's ear catches different parts of the discharge. The part of the lightning flash nearest registers as a rumble first, then sound comes from parts farther away.

THUNDERSTORM
A small or microscale event of relatively short duration produced by a cumulonimbus cloud. Thunderstorm characteristics include primarily thunder and lightning, with gusty surface winds, turbulence, hail, ice, precipitation, moderate to extreme updrafts and downdrafts, and, under the most severe conditions, tornados.

TORNADO
A violently rotating column of air in contact with and extending between a convective cloud and Earth's surface. Tornados are the most destructive of all storm-scale atmospheric phenomena.

TORNADO ALLEY
A geographic corridor stretching north from Texas to Nebraska and Iowa. In terms of sheer numbers, this area experiences more tornados than any other area on Earth.

TROPICAL CYCLONE
A warm-core storm system characterized by a low-pressure center that develops over tropical waters and has an organized air circulation. It produces numerous thunderstorms and strong winds. Depending on sustained surface winds, meteorologists classify the system as a tropical disturbance, a tropical depression, a tropical storm, or a hurricane (typhoon).

TROPICAL DEPRESSION
A tropical cyclone in which the maximum sustained surface winds are 33 knots (38 mph) or less. It may form slowly from a tropical disturbance that has continued to organize.

TROPICAL DISTURBANCE
An area of organized clouds, showers, and storms originating in the tropics, and occasionally the subtropics, that maintains its identity for 24 hours or more. It is often the first developmental stage of any tropical depression, tropical storm, or hurricane.

TROPICAL STORM
A tropical cyclone in which the maximum sustained surface winds measure between 39 and 73 mph (34 and 63 knots). When its winds reach the minimum speed, meteorologists give the system a name to identify and track it.

TYPHOON
The name for a tropical cyclone with sustained winds of 74 mph (65 knots) or greater in the western North Pacific Ocean. Also known as a hurricane in the eastern North Pacific and North Atlantic Oceans, and as a cyclone in the Indian Ocean.

UPDRAFT
A small-scale air current with vertical motion that may create turbulence. If the air contains enough water, the moisture may condense into a cumulus cloud, the first step toward thunderstorm development.

VORTEX
Any circular or rotary flow in the atmosphere that possesses vorticity, when a small air parcel spins as it moves along its path.

WARNING
A forecast issued by the National Weather Service when severe weather has developed, is reported, or is detected on radar. Warnings state a particular hazard or imminent danger, such as tornados, severe thunderstorms, flash floods, winter storms, and heavy snows.

WATCH
A forecast issued well in advance of a severe weather event to alert the public and civil authorities of the possibility of a particular hazard.

WHIRLWIND
A small-scale, rapidly rotating column of wind, formed thermally and most likely to develop on clear, dry, hot afternoons. Often called a dust devil when visible by the dust, dirt, or debris it picks up. Slang for a tornado.

WIND
Air that flows in relation to Earth's surface, generally horizontally. Meteorologists measure four wind characteristics: direction, speed, character (gusts and squalls), and shifts.

WIND-CHILL INDEX
The calculation of temperature that takes into consideration the effect of wind on exposed human skin. Wind chill describes the average loss of body heat and how the temperature feels, not the actual air temperature.

Weather**gallery**

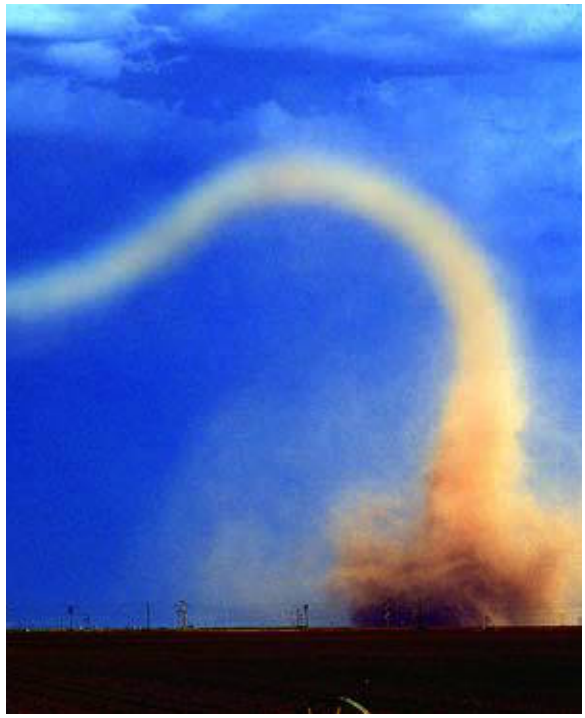
PROFESSIONAL storm chaser Katherine Bay documents a tornado near Sioux Falls, South Dakota, during a twister outbreak June 24, 2003. JIM REED PHOTOGRAPHY

A STORM SURGE and high winds caused by Hurricane Isabel overtake and destroy North Carolina State Highway 12 on September 18, 2003. The surge swept the highway out to sea, transforming Cape Hatteras Village into an island. JIM REED PHOTOGRAPHY

A SPECTACULAR MULTIPLE-STROKE LIGHTNING DISPLAY flashes over Florida in 2004. MARTIN KUCERA/FLORIDALIGHTNING.COM

FLASH FLOODING CAUSED EXTENSIVE DAMAGE to this building. This sequence, from September 29 to October 3, 1983, shows it falling into a river in southeastern Arizona. WARREN FAIDLEY/WEATHERSTOCK.COM

STORM CHASER and tornado researcher Jon Davies photographs a supercell thunderstorm in South Dakota June 7, 2005. JIM REED PHOTOGRAPHY



A CURVED FUNNEL CLOUD and a large debris field were this tornado's features near Littlefield, Texas May 26, 2000. WARREN FAIDLEY/WEATHERSTOCK.COM

WEATHER PHOTOGRAPHER JIM REED battles blowing dirt while documenting a dust storm in western Kansas May 11, 2004. JIM REED PHOTOGRAPHY

SUPERCELL THUNDERSTORMS produce many strong lightning bolts. These two bolts in South Dakota in summer 2007 originated from above the picture's frame, struck the cloud, and continued to the ground. MARTIN KUCERA/FLORIDALIGHTNING.COM

AN INCREDIBLE SUPERCELL appeared June 10, 2006, in northwest Colorado. Notice the intense hail shaft beneath the left side of the cloud. The striations indicate rotation. MARTIN KUCERA/FLORIDALIGHTNING.COM

THIS LARGE WATERSPOUT appeared near Marathon, Florida, August 25, 2007. Research shows that thunder occurs with nearly 30 percent of all waterspouts. MARTIN KUCERA/FLORIDALIGHTNING.COM

ALTHOUGH THESE MAMMATUS CLOUDS don't appear dangerous, such pouch-shaped clouds frequently accompany severe weather, especially anvil-shaped thunderstorm clouds. JIM REED PHOTOGRAPHY

DOUBLE TROUBLE, in the form of two twisters, strikes simultaneously near Sioux Falls, South Dakota, during a tornado outbreak in the central United States June 24, 2003. It was the largest single-day outbreak of tornados in South Dakota history. JIM REED PHOTOGRAPHY

THE FIRST OF A DOZEN dangerous tornados in a late-spring outbreak appears bathed in orange sunlight as it barely misses Attica, Kansas, May 29, 2004. WARREN FAIDLEY/WEATHERSTOCK.COM

VIOLENT WINDS STRIKE KEY WEST as Hurricane Dennis brushes the Florida coast July 8, 2005. Dennis was the strongest hurricane to form before August prior to Hurricane Emily, which struck less than 2 weeks later. MIKE THEISS/JIM REED PHOTOGRAPHY

RIBBON LIGHTNING is seldom seen. It flashes in thunderstorms with high crosswinds and multiple return strokes (from the ground back to the cloud). The wind blows successive return strokes slightly to one side of the previous stroke, causing a ribbon effect. WARREN FAIDLEY/WEATHERSTOCK.COM

CIRRUS CLOUDS develop over a man-made sand dune in western Kansas November 18, 2001. Many cirrus clouds may indicate an upper-air disturbance is approaching. JIM REED PHOTOGRAPHY

A STEEL SINK stands destroyed, wrapped around a tree branch in Moore, Oklahoma, May 3, 1999, the result of an F5 tornado. This twister was one of 66 that broke out across Oklahoma and Kansas that day. JIM REED PHOTOGRAPHY

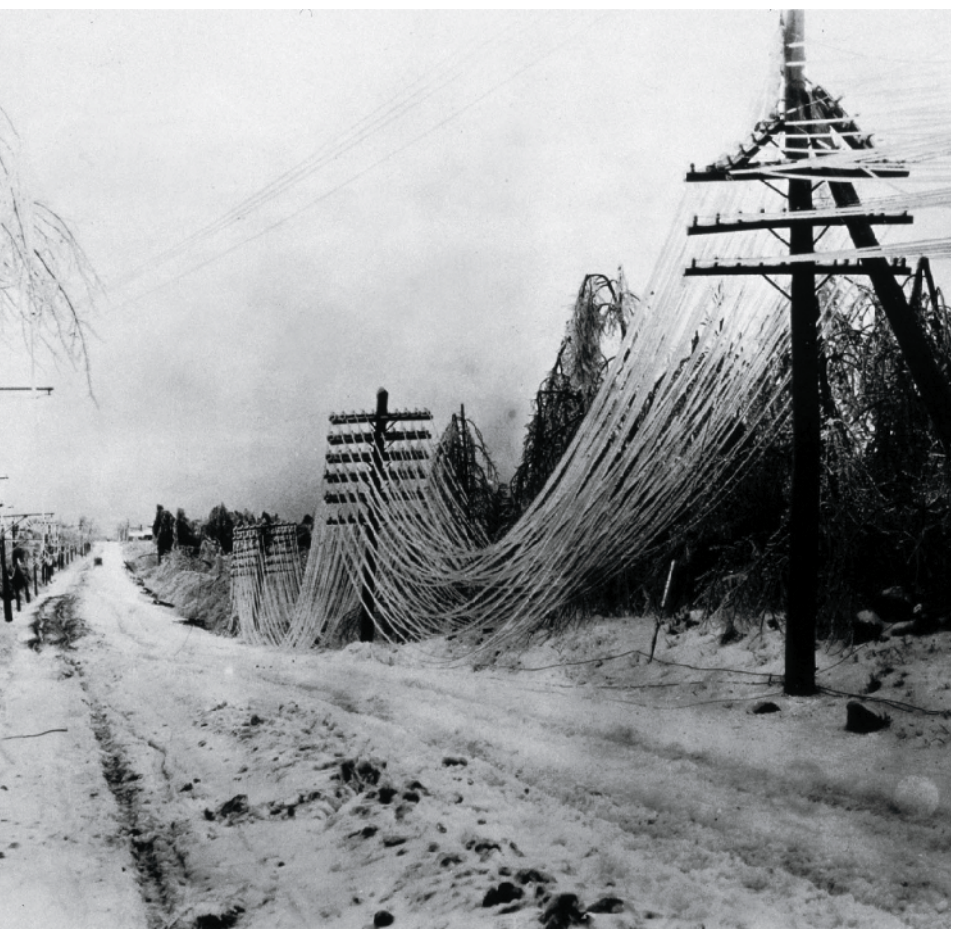
A MAMMOTH HAILSTONE, displayd by Gene Orth of Aurora, Nebraska, plummeted from the sky during a tornadic thunderstorm June 22, 2003. The mass of ice measured 6.5 inches (16.5 cm) across. JIM REED PHOTOGRAPHY

A DUST DEVIL SPINS near Eloy, Arizona. The tiny twisters are rotating updrafts that form during clear or fair weather.
WARREN FAIDLEY/WEATHERSTOCK.COM

A FLASH FLOOD SWALLOWS THIS BULLDOZER in Wichita, Kansas, November 1, 1998. Heavy rain pounded the city for 2 days. Known as the Halloween Flood of 1998, it was one of the worst in Wichita's history. JIM REED PHOTOGRAPHY

LIGHTNING ILLUMINATES A STORM approaching the Florida coast August 19, 2005. MARTIN KUCERA/FLORIDALIGHTNING.COM

A LARGE BELL-SHAPED debris cloud accompanies this tornado as it swirls across a dirt road less than 500 feet from an unmarked Kansas State Trooper patrol car April 11, 2002. This image is a composite created from a high-resolution transparency and a video frame. Photographer Jim Reed then overlapped the two images without manipulating them. The distance, size, shape, and color are authentic.
JIM REED & KATHERINE BAY/JIM REED PHOTOGRAPHY



MULTIPLE LIGHTNING STRIKES flash in front of a reddened sky at sunset near Tucson, Arizona. WARREN FAIDLEY/WEATHERSTOCK.COM

A HEAVY ICE STORM can damage utilities and disrupt transportation. In this image, power and telephone lines sag after an ice storm containing freezing rain. WARREN FAIDLEY/WEATHERSTOCK.COM

TWIN TORNADOS form near Dimmitt, Texas, June 2, 1995. The F4 Dimmitt tornado was then the most comprehensively observed tornado in history. WARREN FAIDLEY/WEATHERSTOCK.COM

A CLASSIC WATERSPOUT appears near the Florida Keys September 10, 1969. Waterspouts are non-supercell tornados that develop over water. WARREN FAIDLEY/WEATHERSTOCK.COM

"A BOLT FROM THE BLUE," which travels horizontally before hitting the ground, flashes September 16, 2006 south of the upper Florida Keys. MARTIN KUCERA/FLORIDALIGHTNING.COM

A THIN BUT BEAUTIFUL early morning waterspout spins just south of Lower Matecumbe Key, Florida, September 4, 2007. This waterspout was already present and fully mature at 6:40 A.M. EDT and dissipated about 15 minutes later. MARTIN KUCERA/FLORIDALIGHTNING.COM

LIGHTNING BEGINS as a discharge from a negatively charged region of water and ice in a thunderstorm cloud. Meteorologists call the discharge path the channel. Many branches can extend from the channel, as in this stroke from August 15, 2005. MARTIN KUCERA/FLORIDALIGHTNING.COM

A LANDSPOUT APPEARS near the Colorado and Kansas border June 1, 2007. A landspout is a tornado not associated with a mesocyclone or thunderstorm. The National Weather Service calls such features dust-tube tornados. WARREN FAIDLEY/WEATHERSTOCK.COM

A MASSIVE THUNDERSTORM produces cloud-to-cloud and cloud-to-ground lightning over Florida August 6, 2006. MARTIN KUCERA/FLORIDALIGHTNING.COM

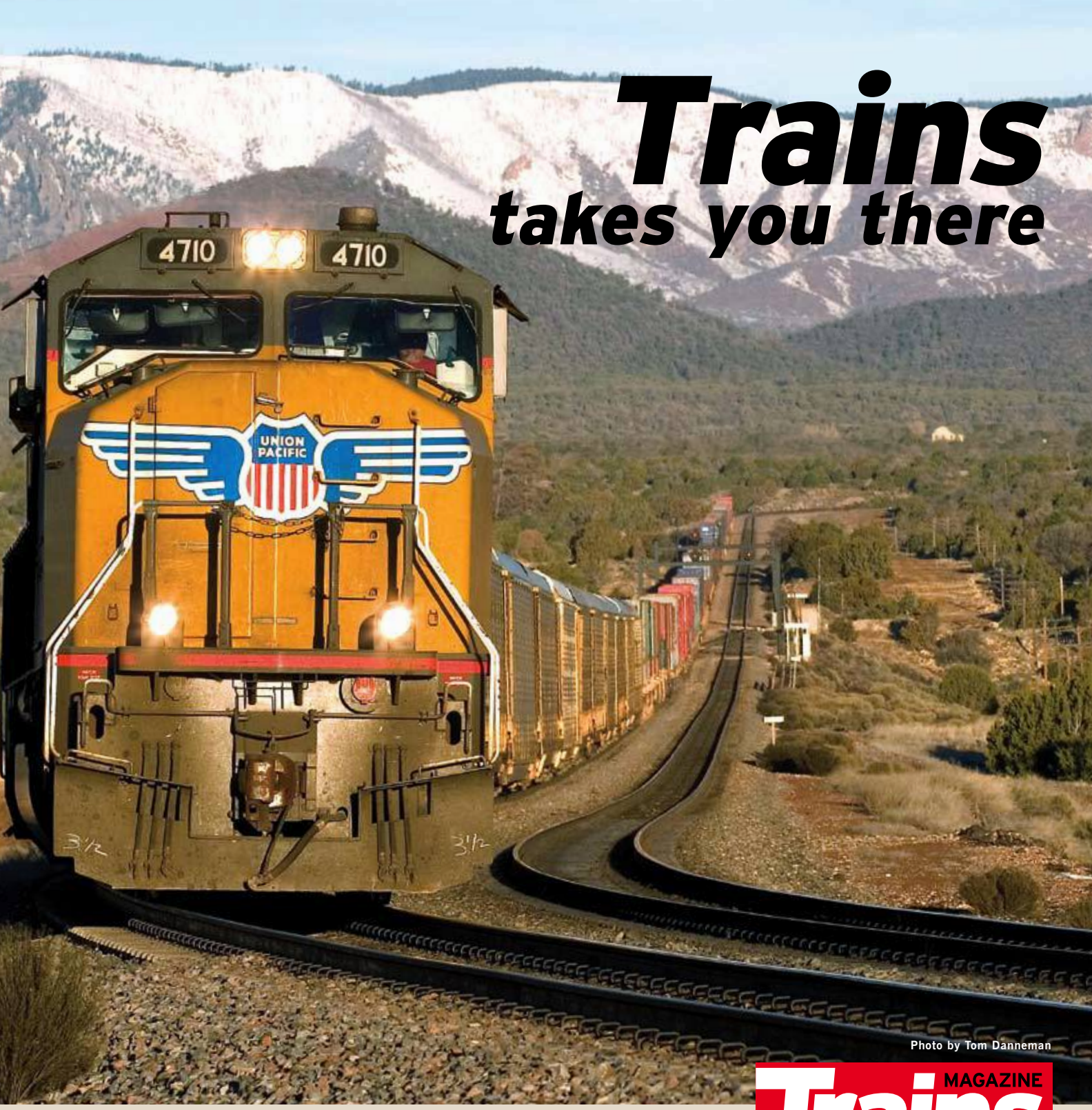
NOT ALL LIGHTNING strikes the ground. This dramatic image of a thunderstorm above Tucson, Arizona, shows cloud-to-cloud lightning. WARREN FAIDLEY/WEATHERSTOCK.COM

A TORNADO drove this large board into the side of a building near Moore, Oklahoma, May 9, 2003. WARREN FAIDLEY/WEATHERSTOCK.COM

A TWISTER SPINS across farmland near Stuart, Nebraska, June 9, 2003. Tornadic activity that day featured two merging thunderstorms, which created a supercell. JIM REED PHOTOGRAPHY

LIGHTNING strikes a residential neighborhood in Wichita, Kansas, August 8, 2007. Lightning heats nearby air to 54,000° F (30,000° C), and it expands, causing a pressure wave heard as thunder.

JIM REED PHOTOGRAPHY



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